SCIENCE SERIES

EDITED BY SIR JOHN LUBBOCK

THE CAUSE OF AN ICE AGE

BY

SIR ROBERT BALL


Ex-libris
Charles Atwood
Kofoid
BMC

Jany/92.

Modern Science Series

EDITED BY SIR JOHN LUBBOCK, BART., M. P.

AN ICE AGE

PUBLISHERS' NOTE.

THE rapidly growing interest in the developments and applications of science in recent years has increased the demand for clear and readable, and at the same time accurate, statements of the work done in its various fields. *The Modern Science Series*, prepared under the editorial supervision of Sir John Lubbock, is designed to supply this need.

The books to be included in this series are intended not so much for the young or for the student as for the educated general reader, who wishes to acquaint himself with the present state of scientific knowledge on the subjects which arouse his interest. To this end each book will be made complete in itself, but at the same time the volumes that deal with related topics will supplement each other. The treatment in each case will be thoroughly scientific, but the subjects will be presented in simple language, as free as possible from technicalities. The volumes will contain about two hundred pages each, and, wherever practicable, they will be illustrated.

The authors will be distinguished specialists, and a sufficient guarantee that the series will fulfill its intended purpose is furnished by the well-known ability of the editor as an interpreter of the results of scientific research.

THE CAUSE OF AN ICE AGE

BY

SIR ROBERT BALL, LL. D., F. R. S.

ROYAL ASTRONOMER OF IRELAND

AUTHOR OF STARLAND

NEW YORK

D. APPLETON AND COMPANY

1891

PREFACE.

As I have written an Introduction to account for the appearance of this book, I have nothing further to say on that subject.

I have only to discharge here the pleasant duty of expressing my thanks to the many friends who have helped me in various ways and degrees by kindly counsel and friendly remonstrance. Their names are Dr. V. Ball, Rev. M. H. Close, Rev. Dr. Crosskey, Prof. G. F. Fitzgerald, Prof. C. Lapworth, Sir J. Lubbock, Mr. A. Rambaut, Prof. W. Sollas, and Mr. L. Steele.

ROBERT S. BALL.

Observatory, County Dublin, *November* 14, 1890.

CONTENTS.

INTRODUCTION.

We are to discuss in the following pages some of those revolutions of which in ages past our earth has been the scene. Perhaps it would be rather more correct to say that we are to discuss a whole series of revolutions, each of which bears a general resemblance to the rest. The date at which our story opens is a very remote one judged by ordinary historical standards. There is not even a tradition to which we might refer which would give the slightest record of these great events; yet when viewed from a geological standpoint the phenomena with which we shall have to deal assume quite a modern character. Ages had already elapsed since the surface of the earth had consolidated. Successive layers of the stratified rocks, up to what we may call the recent period, had been deposited. Numberless races of animals and various tribes of plants had come into being and had passed away before the times of which we write. Indeed, the very animals and plants which at present inhabit our globe had already occupied it. The crust of the globe had approximated to what we now find it, and in all probability the human epoch had begun.

The study of the Ice Age is connected with the two greatest of the natural sciences. Geology has appealed to Astronomy to aid her in the solution of a great problem, and we are now to discuss both the question which the geologists have put, and the answer which the astronomers have given.

I must at the outset express my recognition of the labors of the eminent men who have rendered this inquiry possible. First of all I would mention the honored name of Agassiz, to whose penetration we are so deeply indebted for the means of interpreting the records which the Ice Age has left for our instruction. Then I must refer to Prof. James Geikie ; for who would venture to write of the Glacial Period without having studied and profited by his well-known work, *The Great Ice Age.* It would not be possible for me to mention the names of all the other workers who have contributed to elucidate the subject; but of course the Astronomical theory of the Ice Age must be especially associated with its founder, Adhémar, and its laborious expounder, Dr. James Croll, author of the remarkable work entitled *Climate and Time.*

These acknowledgments having been made, I may be permitted to add that I have ventured to think out the subject for myself. It seems that a serious error has crept into the Astronomical theory of the Ice Age as it is usually expounded. I have shown in Chapter VI how the mistake in the astronomy of the subject arose, and how it came to affect much of the current teaching on the cause of the Ice Age.

THE CAUSE OF AN ICE AGE.

CHAPTER I.

THE RECORDS OF THE ICE.

THE beautiful county of Kerry is pierced by the waters of the Atlantic in a long fiord known as the Kenmare River. On the heather-clad mountain sides which slope down to the water lies a great fragment of rock more than a hundred tons in weight. A lady friend of mine was good enough to take the photograph of this object, from which the frontispiece to this volume has been engraved. The figure standing beside it will suffice to show the proportions of the rock. Even among the peasantry this Cloghvorra Stone, as they call it, is regarded with much interest; and legend assigns to it a miraculous origin.

One who has not pondered on scientific matters might be tempted to think that no special significance attaches to such an object. Is not the whole earth made of rocks? Do not stones abound everywhere, and are they not often bigger than this one? Why should we, then, think more about the Cloghvorra Stone than about the rocks that we can see in the nearest quarry or the stones which pave our streets? A little reflection will, however, show that the interest with which we regard this object is not unreasonable. When we come to examine it we find that the materials from which it is made are not the same as those of the rocks which lie beneath it or immediately about it. Then, too, we observe that lines of rock-bedding are distinctly marked in the stone. They are indicated sufficiently in the picture. We learn from its composition that this rock is a fragment of a series of beds that were deposited at the bottom of the sea untold ages ago. These rocks were upheaved, and then in some way this particular piece was broken from the rest of the mass, carried to a distance, and left stranded where we now see it. A close inspection made a few miles farther up the valley of the Kenmare River will show the same description of rock lying *in situ*. It is impossible to doubt that the Cloghvorra Stone has migrated from its home.

No second explanation of the position of this curious object need be entertained. It were absurd, for example, to say that the stone has lain on the shore of the Kenmare River from all time; we might with equal reason assert that the monuments of Egypt have existed from all eternity. In the case of the Pyramids as in that of the Cloghvorra Stone, we have little or no direct testimony as to their origin. We have to infer both the mode in which the Great Pyramid was erected, and the mode in which the Cloghvorra Stone was deposited, by indirect lines of reasoning. As we identify the quarry from which the Egyptian masons drew their supplies by the fossils which are characteristic of the stones, so we identify the original home of the Cloghvorra Stone by the particular materials of which it is composed.

The problem that first demands solution is to discover the disruptive agent which would be potent enough to rip the Cloghvorra Stone from its parent bed, to bear it down the valley for miles, and to cast it on the mountain side. Here again we may draw an analogy between this question and the similar problem that was presented in the study of the rearing of the Pyramids. We find it hard to conceive how a host of Egyptian toilers could have dragged great stones, each weighing a couple of tons, across miles of desert, and have fitted them together to form the wondrous edifice. What transcendent powers must we attribute to that agent which moved the Cloghvorra Stone! It is fifty times as big and fifty times as heavy as one of the Great Pyramid stones. We should require elaborate levers and screw-jacks to move it an inch; but there was once a power in the Kenmare valley which tossed it like a plaything.

The picturesque site of the Cloghvorra Stone has induced me to choose it as an illustration of a bowlder. But there are multitudes of stones large and small all over the kingdom which excite an interest of the same kind.

In these modern days we have discovered the agent by which these bodies were quarried out and dropped here and there over the country. The power is no longer a mystery. The Cloghvorra Stone was not transported by any human agency; it was not the freak of a giant as local tradition has sometimes narrated; it was not dropped from the heavens as a meteorite, nor was it a bomb projected from a volcano. There is no occasion to regard a bowlder as the consequence of a special effort of miraculous agency; it was ice which did the work.

Ice seems at the first glance to be a material so hard and so unyielding that its behavior in the form of a glacier is not a little surprising. Gigantic masses of ice are not so rigid and unyielding as gigantic masses of stone. We must rather regard ice as possessing many of the properties of a semi-fluid substance. It is more sluggish then either honey or treacle. Its behavior more nearly resembles that of pitch. It must, however, be observed that I do not now enter into any discussion as to the cause of the flow of the glacier. Vexed questions are here involved, which lie, however, wholly outside our argument. For the investigation of the cause of an Ice Age it matters but little what view of the nature of ice movement may be adopted. It suffices for our present purpose to know that even frozen water in vast masses does act somewhat like a fluid, in so far that it creeps gradually downward whenever opportunity for doing so is afforded. A mimic

1

glacier can be constructed by placing a block of pitch at the upper end of a sloping board. In due course the pitch will stealthily descend, thus imitating the movement of the ice down an Alpine valley.

The Swiss glaciers present remarkable illustrations of this property of ice when in sufficient mass. As the more recently fallen snow accumulates in the higher valleys of the great mountains, the weight of the superincumbent portions consolidates the earlier fallen snow which lies beneath. With sufficient pressure the snow passes into the more solid form of ice, and thus the well-known glacier comes into being. Under the intense pressure to which it is subjected the ice commences to descend from the mountain tops to the valleys beneath. The solid river wends its tardy way downward between the mountains. In a river of water the velocity of the flowing mass is greatest at the center and gradually declines toward the sides, where the freedom of motion is impeded by friction with the sides of the channel. The same is the case with the glacier.

The river-like motion of the ice in a glacier has been clearly demonstrated by driving a row of stakes at regular intervals across the frozen current. Initially these stakes may be placed in a straight line, but they will gradually assume a curved form on account of the increased velocity of the ice at the center over that near the edges.

Although the glacier ice is thus seen to possess some of the characteristics of a fluid, it yet retains sufficient rigidity to form in its descent a potent agent for excavation. The icy river in the course of ages has come to occupy a deep ravine between two mountain slopes. It will frequently happen that fragments of rock loosened by frost or atmospheric influences thunder down these mountain slopes and tumble on to the bosom of the solid stream. In the lapse of time the glacier thus becomes freighted at each side with moraines composed of blocks of rock, both large and small, which are often borne in this manner to a distance of miles from their original source. There is also another way in which glaciers possess the power of conveying pieces of stone far from the site in which they have lain since the days in which their parent beds of sedimentary rock were deposited. The icy current flowing slowly over its rocky bed exerts an almost irresistible power upon any obstacle it may chance to encounter. At the bottom of the blue and solid river pieces of stone are occasionally wrenched from the rocky base. Incorporated in the solid ice these blocks of course partake in the glacier motion; nor is their path always such a simple one as might be naturally inferred from the general direction in which the glacier is flowing. Here again we may revert to the phenomena of a river of water for an illustration. In such a river, although the general body of the water tends downward parallel to the direction of the valley, yet the irregularities of the channel will produce eddies and subsidiary currents which occasionally assume a direction opposite to that of the general mass of the water.

We also observe that the water at some points has a vertical component of motion. In that marvelous spot, the whirlpool rapids of Niagara, there is no feature which struck me more than the welling upward to the surface of curious convolutions, due to local and subsidiary currents which have ascended from the deep water.

In a similar manner it would seem as if the equable flow of a glacier down its rocky bed was checkered by the presence of some cross currents which had a vertical component in their motion. In such cases the ascent of the ice in one part of the stream would be of course more or less compensated by a descent at some other points. We are thus able to account for the somewhat paradoxical phenomenon, that though the whole drift of the ice is from the higher level to the lower level, yet it may occasionally happen that a block of stone dug out by the glacier is made so much the sport of some of these subsidiary currents that it ultimately attains an elevation actually higher than that which it originally occupied.

Two adjacent ice rivers will sometimes become confluent, and then the rocky moraines on the two edges that unite will coalesce to form a medial moraine on the augmented glacier. At the present moment every glacier-choked Alpine valley contains innumerable stones, large and small, which have been carried for many years, and have now arrived at considerable distances from their original home.

Let us imagine that the climate of Switzerland has undergone a radical change. Let us suppose that the winters are no longer severe enough to permit the accumulation of the present incubus of snow on the mountain tops. Let us suppose that the glaciers, stinted in their supply from the snowfields above, begin to shrink in dimensions. Let us imagine that the same transformation goes on until the eternal snow has entirely forsaken the Alps, and until a mountain torrent alone occupies each channel down which a glacier now wends its tedious way. When the ice has vanished from Switzerland, what would happen to the rocky moraines which rested on the frozen surface? Their materials would of course lie scattered here, there, and everywhere down the valleys which the glaciers had occupied. Doubtless, as the glaciers shrank in size, many of the rocks which happened to lie on the margin would be detained by irregularities on the mountain slopes. Such blocks may have any dimensions; they may be small as grains of sand, or they may be hundreds of tons in weight.

I have given this illustration for the purpose of showing how we can completely account for the presence of the Cloghvorra Stone on the slopes of the Kenmare River. There can not be a doubt that the Kenmare River was once the channel down which a glacier pursued its way from the highlands of Kerry to the Atlantic Ocean. That glacier has long since vanished, but the Cloghvorra Stone is a monument on which we read its epitaph. The inscription tells us that the climate of Ireland has undergone a transformation like that which we just now imagined to have been applied to Switzerland. The highlands of Kerry are no longer crowned with eternal snow. No glacier now encumbers the Kenmare River. The climate of Kerry is in fact among the very mildest in the United Kingdom; it is in that county that fuchsias attain a growth only to be described as arborescent, and it is in the same neighborhood that the delicate Killarney fern, the prized *Trichomanes radicans*, may be looked for. But the Cloghvorra Stone assuredly tells us that in past ages ice and snow in large quantities existed where now this genial climate prevails.

If other evidence be required as to the past existence of glaciers in the British Islands, it may be provided from many different sources. Let us strive to imagine the aspect which the Swiss valleys at this moment would present were the glaciers to vanish by some transformation analogous to that which has already taken place in Kerry. We have seen that it is in the power of a glacier to rip stones from their bed, and to drag them downward for miles. We can readily understand that such a process must be necessarily accompanied with much violence. The stones forced onward will tear and scrape against the rocky bed. Their corners, occasionally protruding like colossal graving tools from the icy mass, will score and mark the channel down which the excavating machine has been forced. The bed of the glacier must therefore retain abundant indications of the intensity of the forces that the flowing ice has manifested. Here we might expect to find scratches and rude engravings parallel, generally speaking, to the direction of motion. There we should expect to find projecting edges rounded off and salient corners removed. Occasionally we should find portions of the bed smoothed, and sometimes even polished by the vigorous filing, rasping, and sand-papering to which it has been subjected. It therefore appears that for the detection of ancient and now vanished glaciers we have not merely to rely on the presence of erratic bowlders; other indications are provided by the engraving work which the powerful glacier tools have been able to execute.

When regarded as the channels of ancient glaciers, the valleys in the highlands of Great Britain receive a greatly enhanced interest. Every feature that it would be reasonable to expect the glaciers to carve out is exhibited in profusion. The contours of the prominent rocks or hillocks in such valleys are observed to be rounded and smoothed in a way that is at once intelligible if we assume the existence of an ancient glacier. Here we find polished surfaces; there we have long fluted marks and scratches. The eye, instructed to observe them, will find a variety of inscriptions which, being interpreted, record that our islands must have undergone a stupendous change of climate. It is certain that these valleys were once choked up by ice, which has now entirely vanished. The existence of an Ice Age in former times has thus been demonstrated.

I have cited Switzerland for the purpose of illustrating the phenomena of glaciers and of producing an adequate comprehension of the competency of ice to accomplish colossal tasks. We have now to show that the distribution of ice which Switzerland at present manifests, conveys only a very imperfect idea of the severity of the Ice Age of which the Cloghvorra Stone is a monument. For an illustration of the unhappy condition of our country during the existence of the great Ice Age, we must look to some far sterner clime than that of the Alps at the present day. Switzerland is charming, because it is only partially glaciated. Were Switzerland totally glaciated, as the greater part of these islands was once, the playground of Europe would be transformed into an uninhabited region of utter desolation.

The Arctic lands provide an instructive illustration of a region which appears to be at present in a similar condition to that which characterized a large part of Europe at the time of the great Ice Age. Greenland is the country to which we refer. It would seem that ice is perennial in the interior of this desolate land, which bears such an inappropriate name. The Greenland ice is not confined to the summits of mountains which lie above the general level; it is a white sheet overlying the greater part of the country. Here and there along the coast there are some favored spots where openings in the ice-sheet expose the soil, and permit a few hardy inhabitants to maintain a precarious existence. As the winter snows accumulate on Greenland, the glacial sheet becomes gradually thicker, until the pressure of the superincumbent mass forces the subjacent layers into tardy motion. From the high interior, the great ice-sheet gradually creeps downward toward the coast, and thence extends into the ocean. Once the ice-sheet has reached deep water, then, owing to the buoyancy of its material, fragments are broken off and float away as icebergs, which ultimately turn to the condition of water under the influence of the happier climes into which they are conducted by the ocean currents. Such is the origin of those vast icebergs that we find in the North Atlantic. They tell us that a great Ice Age still desolates Greenland and other solitudes of the extreme North.

Little as we know of the Northern Polar regions, we know still less about the dreary neighborhood of the South Pole. It seems, however, that in its vicinity lies an extensive tract which is crushed under an ice-sheet far transcending, both in area and thickness, the pall which lies over Greenland. From the dimensions of the Antarctic icebergs it becomes possible to estimate the thickness of the layer of ice, from the fringe of which those icebergs have broken away. It is now generally believed that the layer of ice which submerges the Antarctic continent must have a thickness amounting to some miles.

The study of the Polar ice-sheets, and of the influence which they have at present upon the land which bears them, illustrates the characteristic phenomena of an Ice Age. Think of the conditions under which an ice-sheet exists. It is of course nourished by perennial showers of snow, and as it grinds slowly onward, we can realize the state of the country which lies beneath its devastating influence. Our comprehension may be quickened by the use of a numerical illustration. Let us assume that 1,000 feet is the thickness of the ice. This is a moderate estimate, for, as we have seen, the sheet under which Greenland is buried has a much greater depth, and the Antarctic sheet far exceeds that of Greenland. Indeed, the ice which once desolated Britain had sometimes a thickness two or three times greater than that which we have supposed. Even with the moderate thickness of 1,000 feet, an ice-sheet would form a terrible engine. Every square inch of the floor over which this frozen ocean plowed its way would have to sustain a pressure of 400 lbs.; every square foot of the country would on an average sustain a load of about thirty tons. This is double as much as the pressure in the boiler of a locomotive engine. Of course the mere incubus of a load, so long as it remained at rest, would not be capable of accomplishing geological work. We are to think of this load, not as resting quietly, but as being thrust slowly onward with illimitable might. In the Alps the speed of the glaciers may be taken as three feet per diem. In the Arctic regions it is ten times as much.

How terrific an engine of destruction such an ice-sheet would be may be shown by an illustration. The base of the Great Pyramid has to support the weight of stone which forms the ponderous edifice. No grinding or destructive work is done on its floor by the pressure of the superincumbent mass, because it lies at rest. But suppose that, by the application of some power of great intensity, the Great Pyramid were to be pushed onward over the desert at the rate of, let us say, a foot a day—think of the awful friction that would be the result. Imagine the grinding and crushing of the soil; think how the rocks would be torn up and pulverized by such an operation.

This may afford some conception of the sufferings endured by a country during the lapse of an Ice Age. An ice-sheet, ponderous in mass and irresistible in power, forms a destructive engine of almost illimitable capacity; by its influence fragments of the living rock are ripped from their bed, crushed to pieces, reduced to mud. Nor is the severity of this cruel treatment mitigated by the brevity of its action. During thousands of years the ice supply is being renewed on the highlands, and the sheet sluggishly descends toward the coast.

It will be noticed that there must be a remarkable difference between the local action of an Alpine glacier confined to a mountain valley and the extended action of a wide-spread sheet of ice which stretches over an entire country. As the Alpine glacier slowly winds its downward way, of course it must grind and pulverize the materials that form the sides and the floor of its rocky channel. Stupendous masses of material have thus been operated on; but in the ordinary glacier such products of the icy mill are not permitted to accumulate. There is a vehicle incessantly at hand which accomplishes their removal. Beneath the glacier a rushing river hurries over the rocky bottom of the ravine. Every visitor to Switzerland will remember the turbid torrent which rushes out from beneath the termination of the glacier. The pigment which has colored this river is the mud which has been ground by the ice.

But the circumstances of a glaciated country overlaid by an ice-sheet are very different from those of an Alpine valley, so far as the destination of the materials which have been ground by its action are concerned. Wherever the ice moves over the higher grounds, the products of the mill will be manufactured. Doubtless there may be occasional rivers beneath the sheet, and such rivers will be engaged in removing some of the materials from their immediate neighborhood. However, the transportation by such rivers must be comparatively local. Only a small fraction of the entire quantity of detritus produced in a country overlaid by an ice-sheet can be removed by such agency. The material is pushed along by the ice till it reaches the lower plains, where it collects, and, except the local scavenging by streams, there is no vehicle by which the growing accumulations can be removed. The rocks offer no hope of escape for the mud below, nor would an exit be practicable through the ice above. We thus see that the products of the stupendous grinding mill must steadily accumulate, and thus in the lapse of ages a cushion of clay, intermingled with stones, is formed between the ice-sheet and the solid rocks of the earth's crust.

At the present moment there can be little doubt that the manufacture of layers of clay by such a process is in actual progress at many places both in the Arctic and the Antarctic regions. The significance of this action of an ice-sheet depends, however, on the fact that such accumulations may serve as monuments to testify to the former existence of an ice-sheet when the ice itself has long since vanished. For suppose that after a country has been thus glaciated for thousands of years, the climate should begin to ameliorate, more ice is melted in summer than is made in winter, so that the sheet begins to lose its ample proportions. The glaciers shrink back to the mountain valleys, and the soil of the low-lying lands is once again bared to sunshine. Though the mild climate may suffice to chase away the ice, yet it is a much more difficult matter to remove the accumulated masses of clay. These will often, in part at least, remain, and their character is so unmistakable that we can point to them as infallible records of what has actually taken place.

You will remember that the existence of erratic bowlders afforded sufficient evidence to prove that many valleys in the highlands of the United Kingdom were once incumbered with ice; we have now learned how to recognize the traces of a far more severe glaciation. We have the best reasons for knowing that a large part of the United Kingdom was once, or more than once, buried beneath an ice-sheet. If I venture to allude to the evidence on this subject which is afforded in the highlands of Ireland, it is because I desire to speak of phenomena which I have had frequent opportunities of observing. The records of the ancient presence of an ice-sheet over a great part of Ireland are of such an unmistakable character that no one whose attention has been directed to the matter can fail to appreciate them. It is true that for the nice interpretation of the more delicate parts of the evidence the skilled eye and the experience of a trained geologist are necessary. To such skill and training I can not pretend, but the more obvious phenomena are so manifest that he who runs may read, and it is to such phenomena that I would specially direct attention.

To one who would study the records of glaciation a visit to Clew Bay, in the west of Ireland, is full of instruction. At the time of the Ice Age an ice-sheet broad and deep invaded the Atlantic. The mountains in the neighborhood display evident marks of the erosion to which they have been exposed. In some cases they have been so much worn as to suggest that a vigorous giant had actually smoothed off their flanks and sometimes even their summits with a rasp. A vast layer of ice-wrought material accumulated on the flanks of the mountains in the way we have described, and much of that layer is there to this day. It is composed of tough and dense clay, largely charged with multitudes of fragments of rock of every dimension up to masses which weigh several tons. It would seem that the layer of the ice-wrought material must have originally overlaid a large part of the coast where Clew Bay is now found. After the ice had vanished, the waters of the ocean invaded the sheet and carved it into a miniature archipelago. A cruise among these islands shows many striking sections through the bowlder clay. This material is so stiff that it will often form cliffs nearly vertical from which characteristic stones of every size and of diverse materials are protruding. If you land on one of these islands you will find the shore composed of bowlders that have obviously been derived from the cliffs. These loose stones on the beach have, of course, been cleansed from clay by the sea, and are water-worn by the friction of the waves. But to study the ice-manufactured material itself you must dig some of its bowlders from the clay, and then carefully wash away the finely wrought mud which adheres to them. It will then be frequently found that the stones are partly worn at the corners, and also engraved and striated in a remarkable manner. The glaciated stone represented in the figure on the following page was obtained on one of these islands in Clew Bay. The markings which it displays can be accounted for if we bear in mind the origin of the bowlder clay. It can not be supposed that these marks were produced by the attrition of the stone on the beach by the waves. The stone

FIG. 1.—A GLACIATED STONE.

was extracted directly from the solid clay in the cliff, and was not picked up from the beach. In fact, the water action on the shore would never have produced marks of this description; it would rather have tended to obliterate them if they had previously existed. Water-worn stones never retain that delicate tracery characteristic of glaciated fragments in the bowlder clay

Though the inscribed stones have obviously been treated at some former time with no little violence, they now repose in peace. Indeed, as they rest, and have rested for thousands of years, undisturbed in their bed of clay, the inscriptions they bear have been carefully protected from every source of injury. The soft surrounding matrix has preserved the most delicate tracery, just as the ashes of Vesuvius have preserved the features of Pompeii. It is now our duty to interpret the writing which these marked stones exhibit. In the first place it is plain that such objects are fragments which have been torn at some epoch from their parent rocks. It is generally possible to point out the actual districts from which certain of these fragments have been derived. Both the material of the stones themselves and the fossils or minerals which they sometimes contain will, in conjunction with other circumstances, enable them to be traced approximately to their sources. We often discover that they must have been dragged for miles, and we are thus enabled to propound the questions which the bowlder clay suggests.

We have to explain how the upper layers of the solid rock over which the ice-sheet moved became crushed into fragments; we have to account for the fact that these fragments were borne for many miles across the country, in the course of which journey they became enveloped in vast sheets of plastic and tenacious clay; and we must show how in some cases they became engraved and scored like that stone we obtained at Clew Bay. No reasonable explanation has ever been offered of these phenomena except that provided by the existence of an ancient ice-sheet. The bowlder clay in Clew Bay, as well as in other parts of the world, was manufactured by the grinding of a deep sheet of ice over the surface of the unhappy regions which it laid waste. As the ice advanced with deliberate movement for ages it gradually interposed a substantial layer of clay, charged with stones, between itself and the living rock.

The navvy often finds bowlder clay an extremely tough material to excavate. Indeed, I believe that contractors would frequently prefer to quarry solid rock itself rather than deal with some descriptions of bowlder clay. The evidence, however, shows that under the influence of the tremendous pressure to which it was exposed by the superincumbent ice, the bowlder clay did actually yield like dough to the forces brought to bear upon it. It is well known in the mechanical arts that many bodies which are ordinarily solid can be made to flow when subjected to the influence of a sufficiently intense pressure. Lead is assuredly a solid, yet under the power of the hydraulic press this metal is squeezed out into leaden pipes. The bowlder clay under the ice-sheet evidently flowed in the same sluggish and tardy manner as lead is made to do in the manufacture referred to.

During the kneading of the bowlder clay by the advance of the overlying ice-sheet, the stones it contained were rubbed and scratched against one another or against the rocky floor. All the characteristic appearances which such stones present can thus be fully accounted for. The asperities on the surface have been frequently removed by wear and tear, and the rounded edges are attributable to the same action. The extent to which the glaciated stones will have suffered from attrition vary in every degree. Some fragments which seem to have been freshly broken off may bear but few traces of the intense forces present in the torpid streams down which they have been borne; others, again, have evidently been exposed to the full brunt of the torrent.

The evidence for the existence of an Ice Age has now been briefly discussed. Three distinct classes of phenomena have been brought into correlation. We have, first, the existence of isolated bowlders like the Cloghvorra Stone, which lie scattered broadcast over the country. We have, secondly, the remarkable way in which the contour of the hills and valleys in glaciated districts have been shaped, while closer examination shows the not less instructive groovings and polishings to which the exposed surfaces of rock have been subjected. Finally, we have the presence of layers of bowlder clay covering vast areas in our Northern latitudes, and charged with multitudes of engraved stones, which require no other explanation than the former presence of the ice-sheet. A theory which presents a satisfactory method of accounting for a multitude of phenomena, apparently so diverse in their nature, demands our careful attention. Especially is this the case when it is borne in mind that we can see even now great ice-sheets in operation in other climes which are for the present less favored than our own.

Provided with the means of tracing the footsteps of the ancient and long-vanished ice-sheet, we can form some conception of its extent and its thickness. Its extent must have been far greater than even the present areas of the bowlder clay, while its thickness is to be inferred from the highest elevations on our lofty mountains at which the indications of ice action have been recognized. It would seem from all the evidence, that a tremendous ice-sheet covered Scandinavia and choked up the North Sea, while the greater part of the British Islands was also buried under ice. Beneath this ocean of ice even the outlying islands of our western coasts were submerged, and beyond them the great sheet extended to some unknown distance into the Atlantic. There, no doubt, an ice cliff opposed a front to the billows of the great ocean, and from thence icebergs broke off and floated away just as they do from the coasts of Greenland or Alaska at the present hour. Into the minuter details of the subject I do not here presume to enter; let it be sufficient to say that the southern parts of England seem to have been spared the fearful visitation by which the greater part of Britain was overwhelmed. In other parts of Europe phenomena of a like description have been observed; and the ice-sheet seems to have extended from the North into Central Europe. The New World also has not been exempted from the desolation which an ice-sheet is competent to produce. Over a great part of North America huge glaciers broad and deep, as befitted the proportions of the continent where they originated, submerged the Northern regions, occupied the basins of the great lakes, and spread as far toward the South, as is fully described in that most interesting work, Wright's *Ice Age in North America.* But we shall not attempt to give many particulars; let us rather present a connected summary of the phenomena, which will be more suitable to our purpose.

On our earth, as we find it to-day, we have at the North Pole an intensely glacial condition, which extends for hundreds of miles around. So severe is the climate that all attempts to penetrate the icy solitude and reach the Pole have been hitherto unavailing. Encircling the Arctic regions we have the temperate regions of our globe, which manifest great varieties of climate, even along the same circles of latitude. Farther South we come to the sunny regions, which seem never to have been invaded by the desolation of an Ice Age. In a similar manner we subdivide the Southern Hemisphere. There is intense glaciation at the South Pole, and there is a temperate region intervening between it and the tropics. Owing, however, to the large proportion of the Southern Hemisphere which is occupied by ocean, and owing also to the imperfection of our knowledge of the geological phenomena of the lands in the south temperate regions, we are not able to speak with the same degree of confidence with regard to the glaciation of the Southern Hemisphere which we have felt when speaking of the Northern. Such is at the present moment the condition of our globe so far as glacial phenomena are concerned. It may be described as the normal condition. We shall presently have to contrast it with the two extreme conditions which appear at some times to have prevailed.

Putting the information together which we have procured, we are now enabled to sketch in some degree the circumstances attending the advent of an Ice Age. We must imagine that the cap of ice and snow which is normal at the Pole commences to enlarge its boundaries. It refuses to remain confined within that Arctic circle, which we are now fortunately permitted to regard as its legitimate home, and it creeps downward and invades the temperate latitudes. Centuries and perhaps even thousands of years must have elapsed before the ice had completely occupied the area destined for glacial devastation. Doubtless the progress was intermittent. The ice-sheet advanced during the winter, it retreated during the summer, but each advance exceeded the subsequent retreat, until at last the southern limits of the glaciated districts were reached. Then some of the fairest regions of our globe lay crushed for ages beneath a superincumbent load of ice hundreds or thousands of feet in thickness. The life, both animal and vegetable, which had formerly abounded in these countries in the days when their climate was still temperate, had necessarily retreated before the encroaching ice, and now sought for generations the hospitalities of southern climes. It was, however, not designed that the desolating presence of an ice-sheet should be eternal. Amelioration began at last to take place in the climate. The ice withdrew each summer more than it had advanced during the preceding winter. Doubtless the transformation was a very slow one. Centuries must have been required before the ice-sheet had completely retreated within its original boundaries, and the climates of the entire hemisphere had regained their normal condition.

CHAPTER II.

THE SUCCESSION OF GLACIAL AND GENIAL PERIODS.

THE records of the rocks, however, sometimes suggest a far more agreeable picture. We have learned that our hemisphere was once covered with ice, but we may also learn that there have been times when conditions widely different have prevailed. The climate has once been more mild and more genial over the Northern Hemisphere than that which it now enjoys. Sunshine and warmth have abounded within the Arctic circle, and, it would seem, as far as the Pole itself. There have been times when Greenland merited the attractive name it bears. A luxuriant verdure has clothed its shores, and stately forests have adorned the land now smothered beneath a thousand feet of ice; even in the vicinity of the dreary North Pole itself, as far as the hardihood of Arctic explorers has carried them, the remains of what seems to have been a charming vegetation have been discovered; plants which are too tender to withstand the rigors of an ordinary British winter without protection, appear at one time to have flourished within a few hundred miles of the Pole. In the Arctic solitudes there were once fresh-water lakes, whose margins were fringed with large reeds, while water-lilies, which demanded a mild climate, floated on their surface. Just as the ice-sheet, when it prevailed during the glacial epoch, suggests a climate incomparably more severe than that which we now possess, so these genial conditions indicate that our hemisphere must have also enjoyed intervals in which the climate was far more benign than that which we at present experience.

I would, then, have you think of our earth, or more accurately of one hemisphere of the earth, as robed from time to time in three different garbs. There is, first, the garb of extreme glaciation which prevails during an Ice Age; the second is one when what may be described as a perennial summer prevails in the land, and extends even to the vicinity of the Pole itself; this we may call the genial garb. There is, thirdly, an intermediate garb, where the climate has neither the severity of the Ice Age nor the mildness of the Genial Age. This intermediate state may be illustrated by the condition in which we find our earth to-day, and in which it has been during the centuries known to human history.

It is necessary to mention at this stage of our discussion that the question has been sometimes debated among geologists as to the simultaneity of the existence of the ice-sheet over different continents of the Northern Hemisphere. No one can reasonably hesitate to believe that Northern Europe was once desolated by an ice-sheet, and no one can doubt but that a similar visitation once made a wilderness of a large part of the North

American continent. It has, however, been doubted whether the centuries during which the ice inundated Europe, were also the centuries during which the frozen deluge inundated America. It has been sometimes contended that the icy invasions were indeed not simultaneous. It has been thought that the ice-sheet sometimes ravaged one continent, and was subsequently transferred to another. The testimony of the rocks is notoriously imperfect; indeed, it is difficult to imagine what the nature of that evidence would be by which such a point could be summarily decided. I think, however, I may say that the weight of opinion, among those best qualified to judge, inclines to the belief that the glacial invasion of the Northern continents took place at the same time. Great Britain and Scandinavia were not alone at the time of their desolation; around Europe and America, around the Old World and the New, the great Ice Age wrapped its deadly mantle.

I may so far anticipate the theory of the Ice Age, which I shall shortly enunciate, as to say that it is of the essence of that theory that the glaciation over a hemisphere shall be simultaneous. In fact, the strongest argument in favor of the simultaneity appears to be deduced from the theory itself. Indeed, if the Ice Ages be not simultaneous—if, for instance, Canada had been in a genial garb while Great Britain was in a glacial one—it would seem wholly impossible to offer an explanation of the phenomena by any physical cause known to us.

It is also an essential doctrine of the Astronomical theory of the Ice Age that the glaciation of the Southern Hemisphere shall be simultaneous over the Polar parts of that hemisphere, just as we have understood it to have been in the Northern regions. Viewing, however, the two hemispheres each as a whole, it is most important to observe that their respective glaciations were *not* simultaneous. This is, at least, the necessary consequence of the Astronomical doctrine, and we look with anxiety to the geological data for any verification of so crucial a point in the theory. The geological facts that can be appealed to on such a question are, it must be admitted, of a somewhat meager character. Indeed, if we will but reflect on the conditions of the problem, we shall find it rather hard to conceive what those facts should be which would demonstrate that when the Northern Hemisphere was glacial the Southern Hemisphere was genial, or when the Southern Hemisphere was glacial the Northern Hemisphere was genial.

It is obvious that the advent of an Ice Age must enormously affect the welfare of organized beings. We have often read how animals flee in terror before the prairie fires in North America; we can equally understand how the sheet of ice, trespassing beyond its accustomed home in the Arctic regions, would drive to more genial climes the plants and animals that inhabited the temperate zones subjected to such an invasion. Whither are these organisms to go? If it should happen that the opposite hemisphere was simultaneously desolated by an ice-sheet, then, indeed, all animals to whom temperate climes were congenial would find their natural habitats very seriously restricted. They would verily lie between the upper and the nether millstone. Suppose, on the other hand, that while one hemisphere was experiencing the rigors of an Ice Age the opposite hemisphere was not glaciated; nay, further, let us suppose that it was not even in its normal state, but that it had assumed that genial garb in which verdure seems to clothe the land from the Pole to the Equator; then this delightful region would seem almost designed to offer hospitality to those creatures which were flying before the ice in the desolated hemisphere in search of a suitable abode. Again, after the lapse of ages another change of condition takes place: the glaciated hemisphere experiences an amelioration of climate. The ice-sheet shrinks back within its normal confines in the Arctic regions, and the contraction of margin and diminution of bulk continues until the ice nearly or totally vanishes, and a genial climate returns to revivify the newly uncovered earth. The reappearance of the former conditions on land and at sea will invite the return to their original home of the plants and animals whose ancestors had been chased away so many centuries ago. We may further suppose that the recall of these emigrants would be accelerated by the fact that the land which had cherished them during their exile had at last become persistently inclement; had begun, in fact, to fabricate an ice-sheet before which organized life must necessarily flee. Thus it would come to pass, when sufficient time had elapsed, that the plants and animals, or rather their descendants, would find themselves re-established in their old home.

It is essentially characteristic of such phenomena that they are periodic. When the fullness of time has arrived, the conditions which produce an ice-sheet are again restored; an ice-sheet is consequently formed, a general emigration again takes place, to be followed, as ages roll on, by yet another immigration. In accordance with this view of the order in which Ice Ages and Genial Ages alternate on our globe, we should expect to find indications of an oscillation of characteristic organic forms between one hemisphere and another. In Darwin's pages will be found some singularly interesting phenomena connected with the distribution of Alpine plants and animals which lend much support to this view.

I have found it necessary to assume the existence of several Ice Ages. It is now convenient to state a little more fully the grounds on which we assert that such remarkable vicissitudes of climate have actually occurred.

The records of the rocks assure us that our temperate zones have not suffered from the icy invasion on a single occasion only. Distinct evidence on this subject is available from several localities. Nor is the interpretation of that evidence a difficult matter. We are in the first place to recollect that after the ice-sheet has melted away, it leaves a deposit of bowlder clay extend-ing far and wide. A more unkindly soil than that same bowlder clay can hardly be conceived; but with a gracious climate, vegetation of some kind will gradually begin to cover the surface, so that, as years roll on, a humus of nutritious soil, charged with organic matter, will establish itself, and verdure will beautify the unlovely material. In the course of time great forests may spring up, and a luxuriant underwood may provide the shelter and sustenance for numerous animals both great and small. A long and glorious genial period has succeeded to the dread ages of glaciation. Again, after the lapse of thousands of years, the scene begins to change. The contrast between the seasons becomes more marked, the severity of the winter becomes significant, and the ice-sheet again begins to creep on with irresistible motion. In its desolating progress it often plows away the stately timber, the underwood, and even the accumulations of rich soil that have appeared after centuries of incessant vegetable growth. Over the surface thus fearfully devastated another layer of bowlder clay will be deposited by the ice-sheet which has laid the land waste.

Historians are often indebted to merely fortuitous circumstances for the preservation of facts of the highest value, and an incidental reference by some ancient writer will frequently in later ages attain an importance that could never have been suspected at the time it was penned. But no historian is more indebted to the casual preservation of facts than is the geologist. The ice-sheet plows away the superficial features of the country, and if this work were perfectly done we should be deprived of information—testimony of paramount consequence—for our present purpose. But it occasionally happens that by some odd chance the disturbance of the soil by the progress of the ice-sheet has been locally impeded. It may have been merely the obstruction of some larger piece of rock, which has slightly checked the local force of the icy current. At all events we find that patches of the surface lie unmolested beneath the bowlder clay which the new ice-sheet has deposited. In a railway cutting, or other section through such a mass, the heterogeneous substance will be occasionally interrupted by some layers of materials more or less stratified, and consisting of a soil charged with organic matter. Such beds sometimes inclose fragments of the plants and specimens of the animals which inhabited the district during the genial period which intervened between the glaciations indicated by the two sheets of bowlder clay. From evidence of this kind we learn that successive Ice Ages have been often separated by genial intervals. Unfortunately, the number of such instances is necessarily very limited. But certain it is, however, that in some places there have been preserved to us successive layers of bowlder clay, duly interrupted by stratified beds, bearing remains of organisms whose place in such a sequence can only be interpreted as evidence of the intervention of genial periods.

It will be convenient if I here set forth a summary of the order of succession of the glacial phenomena of which our earth has been the scene. I have already pointed out that the imperfect geological record does not afford us adequate information on the subject; we are compelled to resort for guidance to the Astronomical theory. It is clear that if this theory be accepted, then, within a period certainly to be reckoned in hundreds of thousands of years, and probably attaining to millions of years, the succession of Ice Ages and Genial Ages, and their relations to the normal condition of the earth, must have been somewhat as follows.

After our globe had continued in a normal state for an extended period of time, during which both hemispheres wore that same garb which they have at this moment, a changed climatic condition supervenes. Over one of the hemispheres, let us say the Northern, the severity of the winters begins to increase, the ice-sheets radiate from the highlands, and the rigors of a glacial period set in. But while the Northern Hemisphere is thus desolated, the Southern does not maintain its normal state; a change of an opposite character is there experienced, so that by the time extreme glaciation has seized the Northern zones in its deadly grip, the Southern have assumed that delightful aspect which we call the Genial Age, in which the rigors of an ordinary winter have been abated, or, indeed, totally cleared away.

But such a state of things is not eternal; the great oscillation continues. The Northern Hemisphere will exchange its climate for that of the Southern. Here I should specially note that we are enabled to offer some numerical facts, which are all the more acceptable inasmuch as they are unhappily rather scarce in the Astronomical theory of Ice Ages. We have sufficient reasons for asserting that when one of these critical periods is in progress, the interval of time between the maximum of an Ice Age in one hemisphere and the next ensuing maximum of an Ice Age in the opposite hemisphere is about 10,500 years. Astronomical data of unchallenged accuracy provide us with these figures. The Ice Age can, however, have no longer reign in the Southern Hemisphere than it was permitted to have in the Northern; another period of 10,500 years will suffice for a restoration of the ice from South to North. Again, another similar period, and the ice will have quitted the North to resume its tyranny over the South. Under such circumstances there will be a succession of Ice Ages, and it must be noticed that while the earth is in this somewhat critical condition, the normal garb of climate is never assumed. Each hemisphere is plunged alternately into extremely glacial and extremely genial conditions, and though no doubt during the transition there may be centuries during which intermediate conditions will prevail, yet such periods can hardly be said to have resembled the normal condition of the globe, such as that which it now enjoys.

A certain cluster of Genial Ages and Ice Ages thus succeed each other in a fashion which we can almost describe as rapid when we bear in mind the extremely protracted character of other great geological periods. At last, however, a change sets in; the intensity of each succeeding glaciation declines, and, doubtless, the alternating genial epochs will have lost some of their charm, until the normal condition of the globe will have become restored. In this state, when the winters and the summers are much as we find them at present, our globe continues for a period that is doubtless to be measured by some hundreds of thousands of years, and Ice Ages and Genial Ages will be things of the far past. After a protracted interval of time, compared with which the duration of an Ice Age or of a cluster of Ice Ages is comparatively brief, the climatic conditions of the earth will again relapse into that acute phase in which a fresh cluster of glacial and genial periods will swing alternately from one hemisphere to the other. Again these acute climatic symptoms will pass away; again will ensue an enormously long period of a perfectly normal climate, until the next recurrence of active conditions.

Thus we see that the ordinary normal climate of the earth is interrupted at long intervals by comparatively brief fits, during which Ice Ages and Genial Ages interchange between the hemispheres. Such is at all events the sequence which the Astronomical theory assigns to the phenomena. I need hardly add that it is necessary to examine with scrupulous care all the definitely ascertained geological facts which can throw any light on the actual laws of the succession of glacial periods. So far as I have been able to learn, the evidence presented by bowlder clay and other traces of the Ice Age can be reconciled with a sequence of phenomena such as we have just indicated.

We can now enunciate in its full significance the magnificent problem which lies before us. It is worthy of every effort we can put forth to obtain its solution. We have to discover why a huge sheet of ice grew over a large part of our hemisphere. We have to show how its existence was sufficiently prolonged to enable that ice-sheet to become hundreds and often thousands of feet thick. We have to show how the forces in action were powerful enough for the ice to plane away the slopes of mountains, and to knead together sheets of bowlder clay often scores of feet in thickness. We have to explain the advent of more genial conditions, and to show how the ice-sheet was chased away and replaced by the charms of a perennial summer. We have to show how the great Ice Age was again, and even yet again, permitted to hold the hemisphere in its lethal embrace, and was again, and yet again, driven back during the vicissitudes of an eternal conflict. Was ever a grander problem presented to the student of Nature?

CHAPTER III.

ATTEMPTS TO SOLVE THE PROBLEM OF GLACIATION.

It has been one of my objects in the preceding chapter to indicate as forcibly as I can the ample extent of the ice-sheets which cover a large part of a glaciated hemisphere. The wide extent of the region laid desolate during an Ice Age is a consideration of the utmost importance when we come to examine the theories which have been offered as an explanation of the phenomenon. In fact, the dimensions of the problem may be regarded as affording a test that can be readily applied to any proposed theory, with the not unfrequent result of consigning to oblivion the theory submitted to the ordeal. No cause can account for an event so stupendous as an Ice Age, unless it contains promise of magnificent accomplishment commensurate with the work to be done.

It is necessary at the outset to glance at the view which is the natural outcome of the revolution in geology wrought by the labors of Lyell. In his ever memorable work, Lyell has sought to account for the great changes in the climates of the earth, by oscillations between the relative positions of the continents and the oceans. If the land on our globe were generally restricted to the Northern and Southern regions, while the oceans were disposed in a broad girdle encircling the earth at the equator, the climates of the globe would doubtless be widely different from those which it would possess if the relative positions of the land and the water were interchanged. There can be no doubt that during past geological periods the disposition of the continental masses relatively to the surrounding oceans has undergone many changes. In the interior of our great continents, and at considerable altitudes on mountain summits, we find unquestionable evidence, in the presence of marine fossils, that sea once occupied what is now dry land. Such interchanges have occurred again and again within geological times, and they were doubtless associated with, and were the causes of, marked modifications in terrestrial climate. It would, however, be unnecessary for our present purpose to enter into any discussion as to the extent to which the temperature or other climatic elements could be affected by any mere rearrangement of the land and water on the globe. This question can hardly be said to be relevant to the theory of the Ice Age, for we must recollect that the times of which we speak, when discussing glacial phenomena, are but of yesterday when placed in their true geological perspective. The stratified rocks indicative of the great geological periods had all been consolidated for unnumbered ages. The strange flora with which the earth had been clothed during remote geological periods had vanished, and the plants that at present adorn our globe had generally taken their places. To a great extent, also, the animals which dwelt on the earth during the last Glacial Period are the animals that dwell with us now, only we should not forget what Mr. Wallace has so forcibly stated, that we live at present in a zoölogically impoverished age, from which many of the largest and the finest animals, such as the mammoths and the saber-toothed tigers, have but recently vanished. We should, however, be probably correct in asserting, that all the animals now inhabiting this globe, man himself not excepted, survived through the last Glacial Period, if not through one or more similar antecedent periods. The outlines of the continents were also much the same in glacial times as they are at present, and consequently the cause of climatic change which Lyell has so ably discussed can not now be appealed to; we are therefore compelled to look for the cause of the Ice Age in some other direction.

So long as we merely think of agencies in operation on this globe itself, it seems hardly possible to conjecture what cause would be sufficiently potent for the production of phenomena so extraordinary. The creation of an ice-sheet which extended over a large part of an entire hemisphere would not admit of the explanation of having been caused by any insignificant agency. But when we come to regard the subject in its true light as having an astronomical origin, we find abundantly adequate forces at our disposal. An ice-sheet is a very great phenomenon from one point of view, and a very small phenomenon from another. The geographer who found regions devastated by its influence, would naturally regard it as an awful catastrophe. To the astronomer, however, an Ice Age will only present itself as a trifling, though no doubt an interesting, incident.

It is surprising to find how the difficulties of the subject vanish when once the solution of the problem is sought in astronomy rather than in geography. The whole perspective becomes changed. No longer do we remember that our earth is a gigantic globe sustaining over a thousand millions of inhabitants; for astronomers regard it merely as a small particle which, with a number of other similar particles, are all performing their voyages through space under the guidance of a great central luminary. In the solar system we already find a potency amply sufficient for such a trifling effort as that implied in the chilling of one hemisphere of a little globe so small that it could hardly ever be sighted from many of the other globes belonging to the same family. The relations between the several bodies in the solar system are such that a very small change, astronomically speaking, might be competent to effect a stupendous transformation in terrestrial climate. Several different astronomical solutions of the problem have been offered, but, with the exception of that with which the names of Adhémar and Croll are so honorably, though somewhat erroneously, associated, they all appear to contain some vital defect.

It is, however, almost unnecessary to add that the Astronomical theory has still some opponents. Doubtless this is partly due to the peculiar position of this subject, as it were on the border-land of two great sciences. There are still some, I believe, who think that the Ice Age has arisen from the interchange of position between land and water. There are some who assert that the Ice Age was caused by excessive heat, just as there are others who say that there was never any Ice Age at all. With every respect for the views of those who hold different opinions, I must be permitted to say that the Astronomical theory seems to offer the only intelligible explanation of the phenomenon in question. It is no doubt true that there must have been many circumstances which tended to modify the climatic changes that have followed from astronomical causes; it is no doubt true that many difficult subsidiary questions arise. There are questions about the laws of radiation and of cooling, questions as to the distribution of land and water, and questions as to the effects of winds and clouds and ocean currents. But none of these details, however important they may be, should be permitted to obscure the broad features of the question. In fact, it might almost be said that the Astronomical theory must be necessarily true, inasmuch as it is a strictly mathematical consequence from the laws of gravitation. Perhaps it would hardly be an exaggeration to assert that even if geologists had not hitherto discovered the Ice Age from its records on the globe's surface, astronomers would have demonstrated by calculation that Ice Ages must have happened, and would even now be urging the geologists to go and look for their traces.

Once we have determined to search for an astronomical solution we can hardly hesitate as to which of the heavenly bodies must first be reckoned with. Considering that the warmth which preserves our life on the earth's surface is due entirely to the sun's beams, it seems inevitable that any vast climatic change such as that of an Ice Age must be connected with some irregularity or variation in the daily supply of sunbeams to warm the earth. Imagine for a moment that our beneficent sun was to withhold his radiation from us. If the genial beams no longer warmed the earth, the temperature of our globe, on its surface, at all events, would begin to fall. Down will the temperature sink until whatever store of heat the earth may have retained on its surface from past sunbeams would rapidly flow away, and in return we should only receive such miserable succor as is afforded by the radiation from the stars. How paltry this would be will be obvious when we reflect on the feebleness of star light as contrasted with that of sun light. Star heat bears in all probability an equally insignificant proportion to sun heat. Down, therefore, the earth's temperature must sink to 100° or 200° or 300° below zero; down, in fact, to the temperature of space; to a point which can hardly be much above the absolute zero of temperature itself. Such would be the unhappy condition of our globe if the sun no longer communicated warmth to us. Now we shall be able to appreciate the full significance of the benefits which the sun confers. His radiation maintains the temperature of our globe at a point which is at least 300° higher than that to which we should be forced to submit if the sun ceased to share with us his warmth. It might indeed be justifiable to say that the temperature of the earth is 400° above that which it would have if the sun were absent. This would of course strengthen the argument on which I am about to enter. I shall, however, to avoid any semblance of exaggeration, be content to take 300° as the basis of my calculation. The degrees are of course Fahrenheit.

The point that I have just mentioned is of such great significance in the Astronomical theory of the Ice Age that I desire to draw particular attention to it. We ordinarily estimate the benefits derived from the sun by the excess of the genial warmth of summer over the ordinary rigor of winter. A temperature of zero Fahrenheit is naturally viewed in our climate as an indication of a winter of extreme severity; but we must remember that, cold as this is, we should be infinitely worse off if it were not for the sun's heat. In fact, the range between summer and winter only corresponds to a very small proportional change in the actual temperature at which our earth is maintained by the sun. Let me endeavor to illustrate this point. I can not assert that the figures I mention are rigorously correct, but there is no doubt that they are at all events sufficiently so for the purpose of enforcing my argument.

Suppose that the average winter temperature in a cold climate were 30°, and that the average summer temperature in the same country were 60°, we might hastily assert that twice as much benefit was received from the sun in summer as in winter. A little reflection will, however, show that this is not at all true; we are led into error, and perhaps excusably so, by having used in our thermometers a zero of temperature which is entirely arbitrary.

The natural zero to be used in discussions on climate would be the temperature to which our earth would fall were the heat of the sun withdrawn entirely. There is, of course, much uncertainty as to the extent to which this point is below the ordinary zero that we employ. We have, however, decided that for our present argument it may lie at, let us say, 300° below that of Fahrenheit. As the summer temperature of the climate we have been describing is 60° above the arbitrary zero, it will of course be 360° above the natural zero. In like manner, the winter temperature of that climate, being 30° above the zero of Fahrenheit, will stand at 330° above the natural zero, which we are now assuming. The summer and winter temperatures are thus 360° and 330° instead of 60° or 30°, as they would be when reckoned by the more familiar standards. We therefore see that the difference between summer and winter corresponds to a comparatively small change when viewed in proportion to the whole range of temperature at which the earth is sustained by the sun's radiation. With sufficient accuracy for the purpose of illustration, we may perhaps estimate the heat which we receive from the sun, by supposing it to be proportional to the temperature at which the earth is sustained when measured from the natural zero. Thus taking the heat received from the sun in summer to be 360°, we find that received in winter is 330°, or only one twelfth less. Of course I do not maintain that the heat received can really be measured in quite so simple a fashion; I merely wish to illustrate the important point that such a range of temperature as we experience between summer and winter only corresponds to a very small proportional change in the total supply of heat which is received from the sun. This point is apt to be lost sight of when we merely express the temperature by units in which the ordinary zero is employed. A fall from 60° to 30° will seem to correspond to a decline of heat amounting to 50 per cent from the source of supply; whereas when we place the zero where it ought to be, it would seem that a deficiency of about 8 per cent in the heat supply would be quite large enough to account for the change between summer and winter.

I have laid particular stress upon this illustration because it is impossible to comprehend the character and the origin of an Ice Age unless the idea which it involves be thoroughly understood. It shows us that though for the phenomena of glaciation a fall in temperature to a considerable number of degrees may be required, yet that such a fall does not necessarily involve any wide departure from the uniformity of our present heat supply. In brief, the argument on which I have been here insisting amounts to saying, that changes in the intensity of the solar radiation of relative unimportance to the sun, may suffice to produce climatic changes of startling, and even appalling, magnitude on the earth.

These illustrations show that the explanation of an Ice Age assumes a comparatively easy aspect when viewed from an astronomical standpoint. A small proportional change in the daily receipt of sunbeams may in its climatic effects be competent to transform this earth from the normal state to the glacial state, while another small change would dissipate the ice-sheet, and make the whole hemisphere glow with the charms of a Genial Period.

We have now to discuss what the cause of the changes in solar radiation may have been. The intensity of the heat which we receive from the sun depends partly on the intrinsic heat of the great luminary and partly on the distance by which we are separated from him. If either the distance of the earth from the sun, or the intrinsic heat of the sun, be altered even to a small extent from its normal value, climatic changes will result; and these changes may seem altogether disproportionate to the cause which has originated them.

In our search for the cause of the Ice Age, we have therefore to examine the possible fluctuations which the sun's heat may experience, and we must also consider the possible fluctuations of the earth's orbit upon which the quantity of the heat which we receive from the sun is dependent.

Is, then, the sun a capricious source of heat? Does he really discharge for us a supply which is at some periods more copious than at others? At a first glance we might think that this may indeed be the case, for there are no doubt some mysterious periodic phenomena associated with the sun which are at present but little understood. The outbreak of sun-spots in certain years attains a maximum, and an undoubted rhythmic succession of such years of sun-spot maxima has been discovered. But it is quite evident that the phenomena here referred to are so brief in their period that they are wholly without any influence on ages so immense as those which glacial phenomena require.

We must also remember the great astronomical truth that our sun is only a star, and we are well aware that among the stars there are not a few which are properly called variables. There are stars whose brilliancy waxes and wanes with more or less regularity; some of them diminish occasionally to invisibility, while at their brightest they are eminently conspicuous objects. Certain classes of variable stars go through a systematic series of changes, and repeat those changes during thousands of cycles with undeviating uniformity. It has therefore been sometimes thought that as our sun is a star, he may also be a variable star. But there is really no substantial ground for such a surmise. It seems almost certain that what we call variable stars are only variable in their light, in much the same way as the beams from a revolving lighthouse exhibit periodic changes to the mariner. The variable star is doubtless in rotation itself, and is attended by other objects which revolve around it. The variableness which it presents to us is certainly in some way a consequence of these rotations, though it cannot be denied that a good deal of obscurity still surrounds the subject. There is not the slightest reason to believe that the alterations are due to any actual shrinkage in the volume of the radiation. What happens is, that a portion of the light is sometimes intercepted or sent elsewhere; thus the variable star appears to change its luster, or sometimes becomes altogether invisible.

This analogy is really of no service in the attempt to explain the cause of the Ice Age. It is perfectly certain that our sun is not at all a variable star in the sense in which we speak of Algol or Mira Ceti as variables. It is also certain that even if the sun did possess a character of this description, the circumstance would give us no aid whatever toward the solution of the particular problems presented by the Ice Age.

I do not, however, assert that from age to age, from one million of years to the next million of years, the radiation which the sun dispenses must be absolutely uniform. Indeed, we know that this can hardly be the case; the sun must obey the same laws of heat which we have studied in our laboratories. Radiation involves loss, and large though the sun is, and intensely heated though it is, our luminary has still only a certain capital of heat available for all purposes. The crash of meteors will, no doubt, serve to supply heat which will compensate, in a small degree, for the torrent which is perennially dispersed by radiation. It can not, however, be doubted that the sun discharges more than it receives, so that at the close of each century it contains much less heat, actual and potential, than it had at the beginning. It seems almost a paradox to say the sun is losing heat, and then to add that it may yet not be falling in temperature. It may be, indeed, that the sun during a large part of its career actually rises in temperature notwithstanding that it is continually losing its heat. I do not now dwell on this matter. I have only introduced it for the purpose of showing that there is no intrinsic variation in the sun's radiation which would account for such phenomena as Ice Ages. The solution of the problem must account for the disappearance as well as for the appearance of Ice Ages, and for the appearance as well as the disappearance of those genial intervals by which successive glaciations have been divided. The changes that are possible in the sun's radiation will not explain such a succession of contrasted phenomena. There can be no doubt that in stupendous periods of time past the intensity of the sun's radiation has performed a deliberate progress. Compared, however, with the changes in the heat-emitting power of the sun through past uncounted millions of years, the coming of Ice Ages and the going of Ice Ages can only be described as the merest flutter. So far as our present inquiry is concerned we may conduct our arguments on the supposition that the intrinsic radiation from the sun has remained at its present value throughout that recent chapter in geological history which treats of the distractions of our globe by glaciation.

I ought also to mention, that there are some other astronomical considerations which have occasionally been supposed to account for the recurrence of Ice Ages. It has been conjectured that while the solar system voyages through space, it may occasionally saunter through warm regions, which will cause it to glow with a genial climate. It seems also to have been thought possible that the path of our system may occasionally have traversed parts of space where the temperature is so much below that found elsewhere, that our globe received a chill which produced a glacial epoch. I confess that these appear to be fanciful notions wholly unsupported by the known facts of astronomy. The temperature of space is rather a vague expression, and I do not feel able to attach any meaning to it, except in so far as it is an indication of the heat received from the stars. If, therefore, our solar system has at any time experienced a space temperature different from that of the region through which it is now passing, it follows that there must have been at that epoch a supply of star heat communicated to the system different from that which it now receives. Let us suppose, for instance, that the system did enter a part of space where the temperature was sensibly higher than we find it now to be. Some of the stars must then have been either intrinsically much hotter or else very much closer to the sun than they are at present. Does there seem any probability that this has been the case? Here is, indeed, an interesting question which touches some of the grandest truths of astronomy.

At the outset of our inquiry we are unhappily rather baffled by a dearth of precise information. We have little or no knowledge of the amount of heat which we at present receive from the stars, though no doubt indications of such heat have been recognized by instruments in the hands of skilled observers. If, however, we regard the heat which each star sends forth as being on the average proportional to the star's brightness, we can make an estimate which will suffice for our purpose. The luster of several of the stars has been carefully measured by photometers, and it has been found possible to express the relation numerically between the light radiated from one of the stars and the light dispensed by the sun himself. It has been shown that the most brilliant star in the whole heavens, the peerless Sirius, sends to us an amount of rays which, though much in excess of those emitted by any other star, require multiplication by a formidable array of figures before they can be brought to equality with those from the sun. Sun light transcends the light from Sirius as received by us in the ratio of 20,000,000,000 to unity. Let us suppose that the sky contains 2,000 stars, each of which transmits to the earth as much heat as Sirius sends us (this is a liberal supposition, for we have exaggerated the total amount of star heat, which is not at all likely to be nearly so much as 2,000 times that of the heat due to Sirius), and even with this assumption it would seem that the total amount of star heat is not the ten-millionth part of that which we receive from the sun. I have shown that a fluctuation of sun heat to the extent of one tenth would be amply sufficient, so far as mere questions of temperature are concerned, either to produce an Ice Age or to disperse it. As, however, the star heat is only one ten-millionth part of the sun's heat, it would seem that unless the capacity of the stars for radiating heat were a million times as great as it is at present, it would not be a factor sufficiently potent to dispel an Ice Age by its presence, nor could the advent of an Ice Age be the consequence of its absence.

It is, therefore, obvious that, with the present relation of our sidereal system to the sun, the stars give no aid in our search for the cause of the great Ice Age.

It would be proper to inquire whether this relation has always been as it is at present. No doubt the twinkling stars are in these days incompetent to exercise any climatic influence. Can it, however, have been possible that a temporary increase in the splendor of particular stars might have been an appreciable source of heat?

Stars of exceptional luster occasionally burst forth in the sky, and they sometimes attain no little brilliancy. Indeed, it has happened that a temporary star has so far outshone all ordinary stars, as to be conspicuous with the unaided eye in broad daylight. But such phenomena, however interesting, render no service to the present inquiry. There has never been an outbreak among the stars, so far as we can tell, sufficiently important to produce the slightest possible effect upon climate; we can not, therefore, look to their variableness for any aid in explaining the occurrence of a great Ice Age.

There is, however, another way in which it might be contended that star heat may have occasionally risen to be a far more important climatic element than it appears to us to be at present. Can our system, in the course of its journey through space, chance to have voyaged into the vicinity of other stars? We know that many of the stars are in actual motion. Indeed, out of all the myriad hosts that the sky contains, it seems inconceivable that even a single one should be found which lies actually at rest. It is no doubt true that many of the stars, or I might say most of the stars, have not as yet exhibited to us an amount of motion which is appreciable by our measurements. As, however, years roll on, one after another exhibits sufficient displacement of its position to arrest the astronomer's attention, and thus the so-called fixed stars are gradually being discovered to be endowed each with its proper motion.

Although the sun is of such unrivaled importance to the earth as the source of our light and our heat, still among the general host of heaven the sun has no more importance than is possessed by thousands of other suns of equal and in many cases of far greater splendor. The sun is but a star around which the planetary system is clustered; nor has the sun a fixity in the heavens which is denied to the rest of the sidereal system. As the other stars are moving, so also the sun is following a definite route through space, and is accompanied in its journey by the earth, and the other planets which own its sway.

When we attempt to express the velocities of star-travel by the ordinary standards of miles per hour, no doubt they seem enormously great. These movements are not, however, to be described as rapid, when we remember the size of the theatre in which such grand phenomena are developed. There can be no doubt that as the stars are moving one and all over the face of the sky, the sidereal heavens must be undergoing a continuous transformation. Its progress is, however, very tardy when estimated by ordinary chronology. The constellations seem to have existed from the remotest antiquity of which any record is preserved. The Great

Bear of which Homer sang is the Great Bear of our skies to-night. The constellations are as old as the hills, no doubt, but have the hills themselves existed from all antiquity? In the progress of geological periods of time, hills and mountains have been upheaved, and hills and mountains have vanished away. The noblest and loftiest of mountain ranges, the everlasting mountains as they seem to our view, are but transient objects, the mere sport of geological forces. The fitful ocean, which ripples to every breeze, preserves its general form unaltered from age to age, while the mighty mountain reared of solid granite, with its foundations deep in the earth, is upheaved in one age only to be dissolved in the next.

The constellations in the sky may be permanent so far as man's observation has extended, but when adequate time is allowed for the stellar hosts to manœuvre, we see that our constellations have no more permanence than have our mountain chains. The family groups of the Great Bear and Orion, as well as the other striking collocations of stars, are undergoing ceaseless transformation. Sometimes the old forms are being relaxed, sometimes doubtless new and picturesque arrangements are being produced. In the course of ages, those stars which adorn the heavens at the present moment must be transformed, nay, must sink into invisibility and be replaced by other stars, forming new constellations which will have no greater permanence.

Considering the transitory nature of all the objects in the heavens, no less than of the objects on the earth, it has been thought that great climatic changes may thus find their explanation. Suppose that, in the lapse of ages, that star which we call the sun shall have adventured so near some other star as to have experienced an increase of temperature; may not great alternations of climate have arisen? It is, indeed, hard to see how such an event, even if it could have happened, would give promise of throwing much light on the occurrence of an Ice Age, though it might conceivably be invoked to provide an explanation of a warm period. It is, however, useless to discuss the matter, for astronomers will not admit the possibility of any approximation between our sun and another star sufficiently close to account for any considerable derangement of the conditions of temperature on this globe. The astronomer remembers that a body can not radiate heat in vast quantities unless that body also possesses considerable mass. Any body possessing mass will exercise attraction on all other objects around. If, therefore, the supposed body were near enough and large enough to radiate appreciable heat, it must also have been both near enough and massive enough to effect quite an appreciable derangement in the movements of the planetary system. The several motions of the planets around the sun are adjusted in delicate relationship. We can not, indeed, assert that external agency has never created a disturbance of the organized arrangements, but we may feel confident that the motions of the planets exhibit no trace of having suffered, even during geological times, any great interference from outside influence. We are, therefore, assured that during such periods as those to which the Ice Age has reference, there has been no close approach of our solar system to any large stellar body. We can not, therefore, believe that any exaltation of the earth's temperature has taken place by approach to a star. We conclude, then, that the circumstances attending the voyage of the solar system through space offer us no aid in attempting to account for the climatic revolutions of the Ice Ages.

We are thus compelled to dismiss the supposition that the changes of geological climate can be attributed to variations in the supply of star heat, still less can we account for such changes by the assumption of fluctuations in the intrinsic intensity of the heat radiated from our own star which we call the sun. Such explanations would certainly, if they could be substantiated, offer a bold and at all events a readily intelligible solution, but there is no such heroic method of dealing with the problem.

We are therefore constrained to look in another direction for the source of the power by which the ice-sheet was generated, and at last we obtain the solution. We shall find it to lie in the fluctuations which from time to time have affected the shape of the path in which the earth performs its annual journey around the sun.

CHAPTER IV.

THE PERTURBATIONS OF THE EARTH'S ORBIT.

A FAMOUS law of Kepler declares that a planet revolves around the sun in an ellipse, and that the sun occupies one of the foci of the ellipse. Did our system consist of but a single planet, this body would at each revolution describe an ellipse of precisely the same size and shape as it had done in each preceding revolution, and as it would do in each succeeding one. The laws of dynamics show that the dimensions of the orbit which the planet pursued could not vary by the smallest measurable quantity. Were our earth a solitary planet revolving around the sun, there could be no astronomical explanation of an Ice Age, and assuredly there would be no Ice Age seeking for explanation.

It is, however, well known that the earth is only one of a considerable number of bodies which revolve as planets around the sun; nor is our globe even one of the more important planets in so far as size is concerned. There are some much larger, such as the great outer planets Jupiter, Saturn, Uranus, and Neptune. Venus is a globe of nearly the same size as, while Mars and Mercury are considerably smaller than, the earth, and there are some hundreds of planets much smaller still. The earth occupies not only an intermediate position as to size, but is also intermediate as regards the situation in which its orbit is placed. There are some planets nearer to the sun, but the greater number, including the more gigantic objects of this class, perform their journeys in paths exterior to that in which the earth moves.

The great discovery of Newton provided a reason for the elliptic motion of the planets. He showed that the attraction of the sun on a planet, in virtue of the law of gravitation, would wholly account for the laws of Kepler. He further demonstrated that no law except that of an attractive force, varying inversely as the square of the distance, could explain the elliptic movement. The force of gravitation was found to account for the movements of the moon as well as for the fall of an apple. Stated generally, the law of universal gravitation asserts, that the attraction between any two masses varies directly as their product, and inversely as the square of the distance by which they are separated. All the principal phenomena of the motions of the planets admit of complete explanation by this theory.

In the solar system the sun attracts the planet, but we must be careful to remember that the latter also attracts the sun. In fact, if the sun and the planet were bodies of equal mass, we could not say that the planet moved around the sun more than the sun moved around the planet; in such a case each body would perform its own elliptic path, and the focus of the ellipse would be midway on the line joining the two bodies. If the masses of the two bodies be not equal, the motion of each will still be in its own ellipse of which the focus lies at the center of gravity of the bodies. In the case of the sun and of the planetary system generally the mass of the central body enormously exceeds that of any of his planets. The sun, for example, is 1,047 times as heavy as Jupiter, the heaviest of the planets; while if the luminary were subdivided into a million equal pieces, the mass of each one of them would be greater than the mass of the earth. It therefore follows that the center of gravity of the sun and of the earth lies close to the sun's center.

The universal law asserts that every body attracts every other body, and therefore there is attraction not alone between planet and sun, but also between planet and planet. Jupiter not only is attracted by the sun, and retaliates by attracting the sun, but Jupiter also attracts the earth, and is in turn attracted by the earth. In like manner there is a mutual attraction between every pair of planets, the intensity of which is measured by the product of the masses of the two planets, divided by the square of their distance apart.

The determination of the motions in the solar system is thus an excessively complicated problem. The path of each planet is no doubt determined chiefly by the attraction of the sun, but it is affected to an appreciable degree by the attraction of other planets. Fortunately for the labors of those astronomers who attempt to compute the heavenly motions, the problem in the case of our solar system has been simplified. The enormous preponderance of the sun's mass over the aggregate of all the other masses in the system, gives to his attraction so great a potency that the planetary movements are nearly those which would result were the other planets absent. A principle with which mathematicians are familiar is here brought into use. There are many problems which can not be solved with absolute mathematical accuracy such as we are accustomed to find in a proposition in Euclid, but which yet admit of a solution which shall possess any desired degree of accuracy short of actual perfection. As a familiar instance of such a problem, I may mention the famous one of determining the circumference of a circle. Every mathematician knows that it is impossible to draw in a mathematical sense a straight line which shall be equal to the circumference, but every mathematician knows also that this limitation of his power involves no practical inconvenience. We can calculate the length of the circumference to a far greater degree of accuracy than would ever be required in any practical application. That would be a large circle of which the radius was equal to the distance from the earth to a fixed star, and yet the circumference of that circle, if its radius be given, can be determined with such precision that the error is under the millionth of an inch. For all practical purposes this solution may be regarded as possessing absolute accuracy.

In a somewhat similiar spirit we attack the problem of gravitation in the solar system. We can compute by successive approximation the effect which one planet exercises upon another, and we can obtain with any required degree of accuracy the changes produced in their elliptic paths by such influences. We speak of the effects thus arising as the planetary perturbations.

Among the most famous problems which have ever exercised the skilled mathematicians, there is none more important than that of the "three bodies." Given two attracting globes, the problem is easily solved, and Kepler's laws afford a complete solution; but when a third body is introduced into the system it commences to attract and to be attracted by each of the other two bodies. The symmetry of the movements entirely vanishes Each body, instead of pursuing an ellipse, will move along a curve of the utmost complexity, which the mathematician finds it extremely difficult, if not quite impossible, to follow. But suppose that one of the three bodies is enormously greater than either of the others, then certain artifices can be employed which bring the problem within the power of human ingenuity to solve. We first determine an approximate form for the track which one of the planets will pursue, and from this we can obtain a more accurate one. A further repetition of the same process will exhibit an orbit still more close to that actually followed, until at last, by what is known as successive approximation, it becomes possible to determine the figure with a degree of accuracy that will suffice for all the needs of astronomy.

In the actual solar system there are also some other conditions which specially tend to the convenience of the mathematical computer. It fortunately happens that all the orbits in which the planets revolve lie nearly in the same plane. It is a further matter of congratulation to the practical astronomer, that the movements of all these planets take place in the same direction. This involves, in fact, a cardinal doctrine in the organization of the solar system. By availing ourselves of these favorable conditions we have been enabled to discover with sufficient accuracy the influence which each planet is capable of exercising on the orbits of the rest.

The subject of planetary perturbations is naturally one of the most difficult in the whole range of science. Every artifice of the skilled mathematician is employed to simplify the work, and the results obtained have amply justified the labor that has been expended. When precise examination of the planetary orbits began to be made with telescopes of optical perfection, and when the lapse of time had enhanced the value of early observations, then it was found that the movements of the planets were not absolutely in accordance with the simple elliptic laws which Kepler announced. It was found that the planet was sometimes a little in advance, was sometimes a little in arrear of the calculated position. It was also discovered that the path which the planet followed was not again exactly traversed during the next revolution. In fact, it was shown by observation that though on the whole the planet moved as Kepler said it did, yet that when we examined minutely the movements which were followed, we found innumerable small departures from the simplicity of elliptic motion.

Such discrepancies are always of value in scientific investigation. We calculate what a magnitude is expected to be, and then we measure what is actually presented to us. The difference between the two can only be regarded as an indication of the presence of some agent which was either overlooked or not accurately allowed for in the process of making the calculation.

The deviations in the places of the planets from those which would be taken by elliptic motion alone have been shown to arise from the mutual attraction between one planet and another. One after another these problems have all, or nearly all, yielded to the repeated attacks of those astronomers who wield the potent weapons of mathematical analysis; their discoveries form some of the most striking chapters in the history of astronomy, and they have a special interest because they illustrate the great law of gravitation, and confirm in a striking manner the evidence on which our belief in that law is founded.

Lagrange, who has been happily termed the poet of mathematicians, has discovered certain beautiful principles in connection with the theory of planetary perturbations. He has shown that the extent to which the perturbations of one planet by the remaining planets can affect its motion, is limited in their extent. This is a proposition of singular interest inasmuch as it involves what is often called the stability of the planetary system. When first the doctrine of perturbations began to receive attention, fears were sometimes entertained lest the irregularities of the earth's orbit should grow to such an extent that a total disorganization of the conditions of life would result. It was thought that possibly the attraction of the great planets, lying as they do outside the earth's path, might succeed in withdrawing the earth altogether from the enjoyment of the sun's benefit. It was also conjectured that a great change of an opposite description might possibly take place by which the earth's orbit would be so contracted that life would be impossible from excessive heat. That neither extreme was to be reasonably feared should be obvious to any one who would look at the evidence of palæontology, which shows that for untold millions of years this globe has been the abode of life. During all that time it has never been exposed to such extremely violent conditions as have been sometimes apprehended. To Lagrange, however, is due the merit of having explained how it is that perturbations have never been able, even in millions of years, to accumulate in the earth's path changes so disastrous. He has demonstrated that the incompetency of perturbations to produce such tragical phenomena is due to a certain organization of the movements of the bodies in our system.

There is a delicate beauty about these celebrated theorems which is sometimes, perhaps, not appreciated to the extent it deserves. The stability of the system results from a particular adaptation of the movements of the planets. The salient features of our system, in so far as the present phenomena are concerned, are three-fold. In the first place, the orbits of all the important planets, though undoubtedly to some extent elliptic, approximate very closely in their forms to circles. In the second place, the planes of all these orbits are very nearly coincident, or are, at all events, inclined at very small angles. In the third place, the directions in which the planets move are all the same. No doubt there are many of the minor planets whose orbits do not conform to these conditions, and the host of comets have orbits which are anything but circles, while their planes are inclined at every angle. Comets and minor planets are, however, bodies of very inconsiderable mass; indeed, it is a significant fact that all the really massive planets in our system, including the earth itself, move subject to the conditions already stated. It has been shown that the stability of our system as a mathematical proposition depends for its proof on the fact that the planetary movements are subject to these conditions.

With respect to a system like ours, it follows from the laws of dynamics that the mutual attractions wheerby each planet seeks to draw aside the other planets from their orbits can never succeed in effecting a permanent alteration either of enlargement or contraction in the diameters of the orbits. The length of the elliptical orbit remains invariable, notwithstanding the influence of other planets. It has also been shown that though the planes of the orbits in which the planets revolve undergo some slight fluctuations in consequence of perturbations, yet no one of the planes can ever attain any large departure from its original position. Finally, and this is the most important point for our present purpose, it has been demonstrated that though the eccentricities of the several orbits fluctuate in response to the perturbing attractions, yet that in no case can the eccentricity of a planetary orbit exceed a certain ascertainable limit.

Thus we see that the competency of perturbations to effect changes in the planetary system is confined within definite bounds. The orbits are now nearly circular; they can never depart more than a certain extent from that form. The dimensions of those orbits as measured by the longest diameters remain unalterably constant, and the situations of the planes of the orbits must always remain in the vicinity of their present situations.

We shall best appreciate the significance of the celebrated mathematical principles which I am here enunciating, if we observe how comparatively slight would be the alterations in our system which would suffice to deprive it of protection against catastrophe. Let us conceive a system consisting of a sun and planets equal in their several bulk and weight to ours. Let these planets all revolve in orbits severally identical with the orbits which our planets pursue. Let the planes of the orbits in the ideal system be situated both as to inclination and as to aspect precisely as the planets of our system; while, to complete the resemblance, we may conceive the ideal system to be supplied with troops of comets and with satellites which revolve around the planets and coincide in every respect with their actual prototypes. It might be supposed that the theorems which guarantee immunity from the accumulation of perturbation to an injurious extent, would also take under their shelter the imaginary system I have supposed. This is, however, not necessarily the case. It may be noted that in our stipulations as to the resemblance of the two systems, no mention has been made of the *direction* in which the planets are to pursue their revolutions. In the actual system all the movements, at least of the important bodies, observe the same direction. If, however, in the ideal system, the direction of motion of even a single great planet, such as Jupiter, were altered, then our expectations of the permanence of the system might vanish. Lagrange's theorems only apply to the case where the movements are all performed in the same direction.

I may give an instance of the remarkable reasoning by which results of this kind are obtained. Let us simplify the system until it consists but of a sun which guides the circulation of two planets not very widely differing from each other in mass. Let the orbits of these planets be nearly circular, and for still further simplicity we may suppose that they lie in the same plane. We first multiply each of the squares of the eccentricities by a certain number, and then add them together. It follows from the laws of dynamics that no matter how much each planet may disturb the other, this total remains absolutely unaltered. If, therefore, the eccentricities of the two orbits were small, either in the beginning, or, indeed, at any time, then this total will be small. It follows that the sum of the squares of the eccentricities, each having been previously prepared for the operation by having numerical factors applied to it, must always remain small. The consequence of this principle is irresistible. If the sum of two things, both essentially positive, is a small quantity, it necessarily follows that each of the quantities by itself must be small; therefore the eccentricity in each of the two orbits, which was small at the beginning, will continue forever small. Hence we receive assurance of stability in the shapes of the great planetary orbits. It appears that they can never depart to any considerable degree from their present nearly circular form. They can never, for example, have their paths transformed into long ellipses like those in which some comets revolve.

Let us note in what particulars our argument would have broken down if the planets did not move in the same direction around the sun. Instead of the assertion that the sum of the squares of the eccentricities was constant when each was modified by an appropriate factor, we should now have to admit that it was the difference between these two quantities which remained unchanged. No inference as to stability would be possible from such a theorem. It is true that each of the two quantities is at this moment small, and therefore their difference is now small, and small it must ever remain. This, however, offers no assurance that the two quantities themselves will remain small; it is indeed obvious that the difference between two quantities might still be insignificant while both of the quantities were enormously great. If, therefore, the directions of the planetary movements were not coincident, there would be nothing, so far as these theorems are concerned, to prohibit the formation of monstrous orbits which would be quite incompatible with the permanence of our system. It can be similarly shown that each of the other articles of the planetary convention is a necessary condition for stability. In fact, there seems every reason to believe that the mere existence of our earth, with its teeming life, for past millions of years would be alone sufficient to require that the orbits must have been conformable to the regulations of the convention. It is hardly too much to assert that if there should be any other great planets besides those already recognized, we might fairly expect from dynamical reasoning alone to find that the orbits of those planets were nearly circles, that their planes were inclined at very small angles, and that the direction in which these planets revolved was identical with that of the planets with which we are familiar. Indeed, such laws were found to be observed by the two new planets, Uranus and Neptune, which have been discovered in the sun's system within modern times

We have now to concentrate our attention on the variations to which the earth's orbit is subject in virtue of the perturbations. The efficiency of the different planets in their capacity to produce disturbance will differ according to their masses and their distances. The disturbance produced by the same planet is moreover always varying both in magnitude and direction. It is, however, important for us to acquire some distinct notion of the magnitudes of the several disturbing agencies; we shall, therefore, for the sake of illustration, express the disturbing force of each planet at the maximum value of which it is capable.

Unparalleled in its luster, the planet Venus is unexampled in the intensity of the pull with which it seeks to make the earth swerve from its revolution around the sun. I have calculated the magnitude of this force, and when expressed in tons the figures that are required baffle our powers of comprehension. The tons in the attraction, or rather, I ought to say, in the disturbing force, of Venus are comparable with the miles in star distances. The force is indeed 130,000,000,000,000 tons. We must, however, impair the effect of this array of figures by comparing it, as we are bound to do, with the central force by which the motion of the earth is guided. Compared with the attraction of the sun the perturbing force exerted by Venus is reduced to insignificance, it merely amounts to the twenty-seven-thousandth part of the sun's attraction. This shows in a striking manner how inconsiderable are the greatest effects of planetary perturbation when the earth is controlled by a force of such colossal intensity as that which pulls it toward the sun.

Next in importance to the perturbations produced by Venus are those which are due to the attraction of the planet Jupiter. The great planet is so much more distant from us than Venus that its efficiency as a disturber is largely reduced. On the other hand, the preponderating mass of Jupiter, which is a thousand times that of Venus, tends to swell the magnitude of his influence. It is sufficient for our present purpose to say that the greatest disturbing effect of Jupiter is about half that of Venus. It would be unnecessary to examine what the other planets can severally do; the disturbances they create are much less than those of the two planets we have named. Yet it may be not without advantage to remember that even the most distant planet, or the smallest planet, tugs at our earth with a disturbing force which, when expressed in tons, is often stupendous and always considerable. Long ere Adams and Leverrier had ever thought of undertaking the calculations of the perturbations which the then unknown Neptune could produce, Neptune had been pulling our earth with a disturbing force which can only be expressed by thousands of millions of tons. Nor does the comparative minuteness of some of the planets render them incapable of generating disturbance, which, though imperceptible when applied to so vast a mass as the earth, still seems of great intensity when compared with more ordinary standards of force. Take, for example, the most insignificant of these bodies so far as size is concerned; it is number 217 in the now ample list of the minor planets, and it bears the name of Eudora. This little object has received very scanty attention from astronomers; it is the merest point of light just visible in a powerful telescope. Like its congeners, Eudora revolves in that broad zone between the orbits of Mars and Jupiter which is tenanted by the numerous host of little planets. Eudora is doubtless only a few miles in diameter, but yet that little body transmits to our earth a disturbance which would seem of startling magnitude if we expressed it in tons. Think for a moment of that superb suspension bridge which stretches from New York to Brooklyn; each of the main cables by which this bridge is supported is composed of a multitude of steel wires, and is capable of withstanding a force amounting to thousands of tons; yet one of these cables would snap like a piece of packthread if exposed to a strain equal to the disturbance produced by Eudora on the earth.

It may also be desirable to glance at the possible disturbances to which our earth may be exposed from bodies lying wholly exterior to the solar system. There are, of course, objects possessing this character in untold millions. They form the host of stars. The magnitude and masses of these stars are such that they would be competent to originate frightful perturbations were it not that they are fortunately separated from us by stupendous distances. Indeed, it may very probably be that the enormous distances of the stars is a necessary condition to the well-being of our system. It is, however, possible in those cases where we know both the mass and the distance of a star to compute the disturbing effect that it can produce. In performing such a calculation it has, however, to be borne in mind that the efficiency of the disturbing force does not follow the simple law of the inverse square that is so familiar in the enunciation of the law of gravitation. We have here to deal not with the absolute amount of the attraction, but rather with the difference between the attraction of the sun by the disturbing planet and the attraction of the earth by the disturbing planet. The disturbing force varies according to the inverse cube of the distance; this, fortunately for our welfare, places the more distant bodies at a special disadvantage in their capacity for producing disturbance.

To examine the possible effect of the stars we naturally take the most brilliant of them—Sirius—which is a million times as distant from us as the sun. If Sirius were but twenty times as heavy as the sun, then it is easy to calculate that the disturbing force that the star will exert on the earth is equivalent to about a hundred tons. This perhaps would be a large force in many terrestrial matters, though engineers nowadays have often to deal with forces far greater.

The mass of our earth is so enormous that it requires a correspondingly gigantic force to produce an appreciable change in its motion. The consequence is that the consideration of many of these minor perturbations may be neglected, at all events for our present purpose; the chief disturbances of the earth's path must be attributed to the influence of Jupiter and Venus. It will therefore be seen that these planets are largely responsible for the production of the Ice Ages.

CHAPTER V.

THE ASTRONOMICAL THEORY OF THE ICE AGE.

OUR investigation of the perturbations has now conducted us to this stage. We see that the earth describes an elliptic path around the sun, and that the major axis of that ellipse preserves its length unaltered in so far at least as the more important class of perturbating effects are concerned. The shape of the orbit, however, undergoes certain changes. Sometimes, from a nearly circular form, the orbit passes by an extremely gradual process into an elipse, and then, in periods of time that are to be told in hundreds of thousands of years, the ellipse gradually again assumes a nearly circular shape. Thus in the lapse of ages we perceive a slow waxing and waning in the ellipticity of the earth's orbit. But let us repeat that even when the orbit has departed to the utmost extent from a circle, it is still not to be regarded as a long ellipse, like, for example, one of those in which a periodic comet would be found to revolve. I represent in the figures on pages 100 and 101 sketches of the path of the earth at a time when the eccentricity has reached the highest degree which it is possible for it to attain in consequence of planetary perturbations.

These changes appear to have profound significance when viewed in connection with those climatic vicissitudes through which our globe has passed, and of which Ice Ages appear to be among the latest manifestations. It would, therefore, be necessary to examine carefully the possible thermal changes that can result from variations in the eccentricity. It is the more desirable to attend specially to this matter, because at a first glance it would appear to be an utterly inadequate explanation of any considerable climatic effect. There can be no doubt that when the eccentricity is at its highest point the earth is, on the whole, rather nearer to the sun, because while the major axis of the ellipse is unaltered the minor axis is least. It can be demonstrated that the total quantity of heat which the earth receives during each complete revolution will be inversely proportional to the minor axis of the ellipse.

Considering the extremely small changes in the minor axis, it is evident that the total quantity of heat received by the earth during each revolution can only vary by a very small fraction of the whole. The thermal effect of this variation seems so insignificant that it has often been concluded, not—perhaps, without plausibility—that changes in the eccentricity of the orbit were inadequate to account for such stupendous phenomena as Ice Ages. There can be no doubt that the total heat received during the year by the earth does undergo only an insignificant variation in direct consequence of the changes in the eccentricity. The material point for our present purpose is not, however, the total quantity of heat which the earth receives in a year; of far more significance is the distribution of that heat during the various seasons and over the different parts of the globe. It might, for instance, happen that during one season there might be a great exaltation in the daily receipt of heat, but that at the opposite season the heat might be received so sparingly that the average for the whole year would remain unaltered. It might also happen that in certain seasons one hemisphere would receive far more than its daily share of sunbeams and the other correspondingly less, and yet this inequality, so potent as a climatic agent, might not be at all perceptible in the total quantity of heat received during an entire year. It is, therefore, incumbent on us to scrutinize narrowly the effect which changes in the earth's eccentricity can have on the supply of heat at different seasons, and on the shares of that heat which each hemisphere shall receive. We shall presently find that the inequality of the distribution of heat, arising from this cause, attains an importance which would hardly have been anticipated from the very narrow limits within which the fluctuations of the eccentricity are confined. It fortunately happens that a little geometry will serve to pilot us through the mazes of a subject that would be very difficult to trace with a less certain guide.

Let us first discuss the question as to the amount of heat which the earth receives at the several parts of its orbit. We shall here speak of the earth as a whole, reserving to later paragraphs the important considerations which arise when we examine the distribution of the heat between the two hemispheres. If the earth's orbit were truly a circle, then the earth's movement would be uniform around the circumference; and, the distance from the sun being unaltered, the heat received on one day would be the same as that received on every other day. The earth's orbit is, however, not a circle but an ellipse, and therefore it is by no means obvious what the total daily receipt of heat should be. At some seasons the earth is nearer to the sun than it is at others, and, of course, the nearer the sun the larger is the share of heat which the earth obtains. The figure on page 82 may be taken to represent the path of a planet around the sun at the focus F. Draw any two rays, A X and B Y, through that focus, and let us study the heat which the planet receives while it passes from A to B and also while it moves from X to Y. It will be noticed that I have so placed these lines that the part A B is comparatively near the sun, while the other part, X Y, is as far as possible from the sun. During its passage from A to B the planet is submitted to excessive radiation on account of the sun's proximity. On the other hand, while the body is moving from X to Y it is very much farther from the sun, and the warmth which it receives is correspondingly less. We might, therefore, rather hastily conclude that the total quantity of heat received by the planet while passing from A to B would exceed that which it would gather up between X and Y. This might be true if the planet were exposed between A and B for as long a time as that which it takes in passing from X to Y. But this is not the

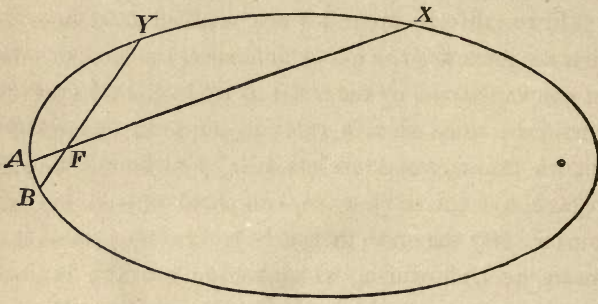

FIG. 2.—AN ELLIPTIC ORBIT.

case. The planet moves more quickly when near the sun than when more remote; it therefore sweeps across from X and Y in much less time than it takes to pass from A to B; in consequence it is submitted to the higher temperature for a shorter time than it is to the lower. Indeed, it can be proved from Kepler's second law, that the intense radiation experienced in the passage between A and B affords to the planet precisely so much heat and no more than that which it obtains during the journey from X to Y. We can express this law still more simply by saying that the heat received while the planet is traversing the arc A B equals that which it receives in traversing X Y. This proposition can be extended to show the following general principle: Draw any straight line, A X, through the focus of an ellipse, then the heat received by a planet in passing round the part of the ellipse on one side of the line is equal to that which it obtains while passing around that on the other.

From this theorem we are enabled to deduce the first important principle which makes clear the effect of eccentricity on climate. It is convenient, in the discussions connected with this subject, to divide a twelvemonth into two seasons instead of into four. We shall regard the entire year as composed of summer and winter. By summer, in the Northern Hemisphere, we mean the time during which the sun's center is above the Equator, while winter in the same hemisphere is defined to be the period when the sun's center lies below the Equator. When summer prevails in one hemisphere there is, of course, winter in the other. Let the line A X in Fig. 2 represent the line of the equinoxes, then it is summer in the Northern Hemisphere while the earth moves around through A B X, and it is winter in the same hemisphere while the earth moves back to its original place through X Y A. Hence we learn the important fact that the total heat received by the earth from equinox to equinox while moving round one part of the orbit, is equal to that received by our globe while completing its journey round the remaining part. To illustrate this principle by a somewhat extreme case, let us suppose the line of equinoxes to be represented by A B in the adjoining Fig. 3. The high degree of eccentricity in this ellipse makes the length of the part A X B very much less than that of the remainder, A Y B. The total heat received by a planet in its passage around A X B will equal that received during the passage around A Y B.

There is another important result which follows from strict geometrical reasoning. It relates to the distribution of heat between the two hemispheres, and

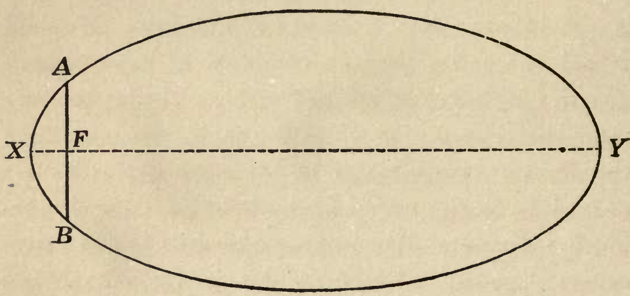

FIG. 3.—AN EXTREME CASE FOR ILLUSTRATION.

may be thus stated: the total amount of heat received on the Northern Hemisphere *in the year*—i. e., in summer and winter taken together—is equal to that received on the Southern Hemisphere.

Of course, if our earth were revolving in a circle around the sun this theorem would be obviously true; the simplest consideration of symmetry would show that both hemispheres had in the course of the year gone through precisely the same relations to the sun. When, however, we remember that the orbit may be elliptical, and that the position of the line of equinoxes may lie across the ellipse in any direction, the result is by no means obvious; it is rather to be regarded as a striking and significant theorem. Refer, for example, to Fig. 3; the Northern Hemisphere will, in that case, have a short and intensely hot summer and a long and intensely cold winter; the Southern Hemisphere will enjoy a long and mild summer and a short winter, the severity of which will be mitigated by proximity to the sun. Notwithstanding these great differences between the seasons and the climates of the two hemispheres, the total quantity of heat which each receives would be absolutely the same. If we take 200 to represent the share of the sun's radiation which the entire earth is able to grasp during the course of the year, then, whatever be the eccentricity and whatever be the line of equinoxes, 100 will be the share of heat received by the Northern Hemisphere and 100 the share received by the Southern.

Up to the present it would almost seem as if we had been striving to illustrate how slight was the effect which changes in the earth's eccentricity were competent to produce on climate. Have we not shown that the total quantity of heat received by the earth in the course of the year is practically invariable? Have we not also shown that the total heat received by the earth during one season (equinox to equinox) is equal

7

to that which it receives in the other, no matter what be the eccentricity, or where the equinoxes may lie? Nay, have we not further shown that no degree of eccentricity and no position of the equinox can disturb that fundamental law which asserts that each hemisphere receives its due half of the total sunbeams of the year? It seems, therefore, hardly surprising that some should have drawn the erroneous inference that changes in the eccentricity could produce no appreciable effect on climate. Closer examination will reveal the irregularities of heat distribution which changes of eccentricity are capable of originating.

At this point I have to introduce a theorem which throws much light on the subject. The demonstration can not be obtained without the use of mathematical symbols, and I have accordingly relegated it to the Appendix; but we shall here enunciate the important result to which it leads us. It being granted that 100 is the expression for the total quantity of heat received on, let us say, the Northern Hemisphere in a year, it is required to determine the shares into which it is to be divided, if they are to represent the heat received during summer and winter respectively. At first sight it might seem that the distribution would depend upon the eccentricity of the orbit, and would also be affected by the situation in which the line of equinoxes was placed with reference to the axis of the ellipse. It fortunately happens that these elements are found to disappear in the course of the calculation.

The shares into which the total heat of the hemisphere is divided between summer and winter remain unaffected both by eccentricity and by the position of the line of equinoxes. The datum in our system on which the distribution does depend is the obliquity of the ecliptic. It will be, indeed, obvious that the obliquity must form a significant factor; for if we should suppose the obliquity to be zero, so that the ecliptic coincides with the equator, the distinction of seasons as we now understand them would vanish altogether.

Amid so much that is changeable in the planetary system, it is fortunate that the obliquity of the ecliptic may, for our present purpose, be regarded as practically constant. It is, no doubt, true of the obliquity as of every other astronomical element, that absolute constancy is not to be expected. But it will be easy to show that, so far as the present investigation is concerned, we are entitled to overlook the operation of the minute changes of the obliquity which arise from planetary perturbation. At the present time it is admitted that the obliquity of the ecliptic is slowly declining. According to Powalky, the magnitude, which at present we take to be 23° 27′ 22·3″, is decreasing at the rate of 47″ per century; that is to say, very nearly half a second per annum. Small as this rate of change undoubtedly is, it might yet be capable of accomplishing immense alterations in the element it affects during the vistas of time that geology opens up to us, and consequently in the climatic conditions of our globe. It is, therefore, of importance to observe that the diminution of the obliquity of the ecliptic does not proceed constantly; it is, indeed, in the nature of a periodical fluctuation, which goes through its changes with such extreme slowness that for practical purposes we may speak of the rate of alteration as remaining uniform during the mere centuries or thousands of years with which human affairs are concerned. Laplace has shown that the obliquity of the ecliptic fluctuates through a range whose limits are about three degrees apart. Further investigation has been made on this subject, especially by Stockwell, who was enabled to use much more accurate data than those which were available to Laplace. Not only were the masses of the planets better determined when Stockwell's work was accomplished, but the influences of Neptune could also be taken into account. The result of his inquiry tended to contract the limits which Laplace had assigned to the fluctuations of the obliquity of the ecliptic. According to Stockwell's determination this element can never sink below 21° 58′ 36″, and it can never rise above 24° 35′ 58″; so that the range according to this astronomer has been reduced to 2° 37′ 22″. It will thus be seen that at present the obliquity of the ecliptic lies not far from midway between the extreme limits which it is capable of attaining.

I entreat the particular attention of the reader at this stage of the argument. Especially would I warn him from falling into the error by which some previous writers have been led sadly astray. What I have shown is, that the heat received *on the whole earth* from vernal to autumnal equinox equals that received *on the whole earth* from autumnal to vernal equinox. Do not read this as if it asserted that the heat received during summer is equal to that received during winter. This is not true, but it has been often asserted. It is, in fact, the fundamental error which has vitiated the Astronomical theory of the Ice Age as previously presented, and which it is the chief object of this little book to expose. As, however, this is the great stumbling-block, I shall spare no pains to elucidate the point, so as to distinguish as clearly as I can between the remarkable law which is true, and the incorrect statement which bears such a specious resemblance to the truth that the two have been frequently confounded. It is obvious that summer in one hemisphere is winter in the other; therefore, when we speak of the heat received during summer, we must, of course, have one particular hemisphere in view. Think, then, of the Northern Hemisphere. It receives a certain quantity of heat during the passage from the vernal equinox to the autumnal equinox—that is, during the summer in the Northern Hemisphere. It also receives a certain quantity of heat between the autumnal equinox and the next vernal equinox—that is, during the winter in the Northern Hemisphere. But these quantities are NOT equal, as has been frequently supposed. The true Astronomical theory is mainly dependent on the accurate calculation of the figures in this part of the subject, so, on the first allusion to them, I request the special attention of the reader. As the work proceeds, he will find the requisite detail added, which it would be hardly convenient to insert in this place. I shall, however, at once enunciate a fundamental truth, which I commend to the earnest consideration of those who do not wish to miss the cardinal feature of this book.

Of the total amount of heat received from the sun on a hemisphere of the earth in the course of a year, 63 per cent. is received during the summer and 37 per cent. is received during the winter.

There must be no mistake about these numbers; they are sixty-three and thirty-seven; nor must there be any mistake as to their significance. They depend on the mathematical calculation given in the Appendix; they admit of no dispute; they are perfectly determinate and certain elements in the theory. If it should prove that the facts which these numbers imply have not been given by any previous writer, then their announcement is the novelty in this book—the one central feature by which it is to be judged. My chief object is to emphasize the relation of these figures to the Astronomical theory. This theory will be entirely misunderstood unless the facts signified by these numbers are borne in mind. No one can discuss the Astronomical theory of the Ice Age unless the figures 63 and 37 form a portion of his consciousness and the refrain of his every argument.

Imagine any elliptic orbit around the sun, no matter what may be its eccentricity; imagine a planet revolving in this orbit with an inclination between its equator and the plane of its orbit equal to the obliquity of the ecliptic at the present moment. There is, of course, an infinite number of varieties in the arrangement of the seasons on such a globe. They correspond to the various positions in which the plane through the center of the sun parallel to its equator intersects the plane of the ecliptic.

For instance, we might represent the line of equinoxes as lying along the major axis of the orbit. The two seasons of summer and winter would then be equal in duration, and the two hemispheres would have precisely parallel conditions as to climate; while it was summer in one it would be winter in the other. The summer in the Northern Hemisphere would be identical in character with the ensuing summer in the Southern Hemisphere. Regarding, as before, the total radiation received by one hemisphere in the course of a year as 100, then the shares received during summer and winter respectively would be 63 and 37. This would necessitate a considerable climatic difference between different parts of the year, for the two seasons are of equal length, and yet one of them receives but 37 measures of heat, while the other obtains 63.

A wholly different case is exhibited in Fig. 3, page 84. In this case the line of equinoxes is perpendicular to the axis major of the ellipse, and divides the path into two very unequal portions; and we shall suppose that the Northern Hemisphere is turned toward the sun, while the planet is moving through A X B. Summer will, therefore, be enjoyed by the Northern Hemisphere during the time occupied by the journey from A to B, when winter sets in and continues during the completion of the rest of the orbit. The Northern Hemisphere will, in this case, have a brief summer and a long winter. Indeed, we can offer a double reason why the durations of the two seasons are so very unequal. In the first place, the length of the journey which the planet has to perform during the winter is longer than that which it pursues during the summer. Secondly, according to Kepler's law, by which the radius from the sun to the planet sweeps over equal areas in equal times, the pace at which the planet winds round the end of the ellipse near the sun is much more rapid than that at which it traverses the distant parts of its path. Both causes will thus protract the duration of winter as compared with that of summer. Yet, notwithstanding the wide difference between such a movement and that previously considered, it still remains true that 63 per cent. of the sun's heat is received by each hemisphere in summer, leaving only 37 per cent. for the winter. It will be noticed that though the summer was brief and the winter was long, yet the planet was so near to the sun during the summer of the Northern Hemisphere that the increased proximity to the source of heat compensated for the brevity of that season, and thus permitted that law to be observed which declares that 63 per cent. of the total year's heat on a hemisphere will be received by that hemisphere during its summer, leaving the remainder to suffice for the winter as it best may.

It will be also instructive to ponder on the condition of the Southern Hemisphere in the case last considered. At the extremity, X, of the orbit the Southern Hemisphere is turned away from the sun, and winter will reign during the movement around A X B, while the same hemisphere will enjoy summer so long as the planet is completing its orbit by moving through B Y A. The seasons in the Southern Hemisphere will therefore be of a wholly different type to those of the Northern; the winter will be short, the summer will be long. The severity of the brief winter will be mitigated by the circumstance that the planet at that season is comparatively near to the sun. The heat of the long summer will be tempered by the circumstance that it is radiated from a sun at a distance above the average. To obtain the figures a certain numerical estimation of the particular facts of the case has to be made. The diagram in Fig. 3 represents an orbit far more elliptical than the orbit which is actually that of the earth. The true shape of the earth's orbit will be seen in Figs. 4 and 5. However, if the obliquity of the ecliptic be 23° 27′, as it actually is for the earth, then, no matter how extreme the eccentricity of the ellipse, the law of distribution of the total sun heat between the two seasons will remain unaltered. The length of the summer and the brevity of the winter, accompanied by the unusual mildness of both seasons, will preserve the observance of the law that 63 measures of the sun's heat are conferred during the summer on the Southern Hemisphere, while 37 are left for winter.

Finally, let us take the case represented in Fig. 2, page 82, where the line of equinoxes, A X, crosses the ellipse, in a direction which we may describe as being at random. During the passage around A B X it will be summer in the Southern Hemisphere and winter in the Northern. The climatic conditions, too, will be somewhat intermediate between those sketched in the last two cases. The contrast between summer and winter will neither be specially accentuated nor will it be well-nigh removed; one feature, and one alone, remains constant during all varieties of circumstance, and that is, the oft-repeated statement that, so far as direct radiation from the sun is concerned, each hemisphere can only obtain 37 measures of heat during its winter, and 63 in summer.

So far as the present argument is involved, the chief effect of eccentricity on the orbit is to assign the lengths of the seasons. As the earth passes from one equinox to the other, there is summer in the Northern Hemisphere and winter in the Southern; while as the voyage is completed which brings the earth round to where it was at first, there is winter in the Northern and summer in the Southern Hemisphere.

For the theory of the Ice Age we require to examine particularly the cases in which the disparity in the lengths of the seasons shall be the utmost possible. This will occur when the line of equinoxes is perpendicular to the axis major of the ellipse. This line divides the ellipse into two unequal segments, while the fact that the earth moves with a quicker pace round the small segment than round the large one further tends to increase the inequality between the number of days of summer and the number of days of winter respectively. We can give expression to the difference between the lengths of the seasons in this highly specialized case in a simple manner. The number 465, multiplied by the eccentricity, expresses the difference in days between the length of the two seasons. For example, with the present eccentricity of the earth's orbit, the greatest possible difference between summer and winter would amount to 33 days. I do not mean that the actual disparity between summer and winter at the present moment is so much as this; it only, in fact, amounts to 7 days, because at present the line of equinoxes does not happen to be adjusted in the manner described.

The line of equinoxes does not, however, occupy a constant position. The well-known phenomenon of precession arises from the circumstance that the line of equinoxes revolves around the plane of the ecliptic. It will, therefore, happen from to time that the line of equinoxes will come to occupy every conceivable position with regard to the axis major of the earth's path. If the position of the ellipse itself in its plane were a constant one, the recurrence of the epochs when the line of equinoxes was perpendicular to the axis major would, of course, be equal to that of the precession of the equinoxes. The matter is, however, somewhat complicated by the movement of the major axis itself. As planetary perturbation affects the eccentricity of the ellipse, so also it affects the situation of its axis. The direction of this motion is opposite to that of the line of equinoxes, and consequently the time of a complete revolution relatively to the ellipse is somewhat reduced.

It follows that about every 21,000 years the line of equinoxes is so placed with reference to the elliptic path of the earth that the difference in duration between the two seasons attains a maximum; what that maximum is depends, of course, upon the eccentricity of the orbit at the time.

It is of importance at this stage of our inquiry to investigate the range of the fluctuations to which the eccentricity is liable. We here touch upon a mathematical inquiry of no little difficulty; it is, however, possible to solve the problem which is thus stated. Given all the masses and the other necessary data connected with the solar system, it is required to determine the greatest eccentricity that the earth's orbit can assume under the disturbance arising from the influence of the other planets. This problem has been solved, and the mean between the different determinations of its maximum value may be adopted. This shows that, when all circumstances combine to accentuate as much as possible the difference in the lengths of the seasons, one of them may be 199 days long, and the other 166; the two together making up, of course, the entire year of 365 days.

It is not, however, to be supposed that whenever the eccentricity attains its greatest value the difference between the lengths of the seasons must necessarily be so large as 33 days. It is only when the requisite direction of the line of equinoxes and the maximum degree of eccentricity conspire, that so great a difference between the length of summer and that of winter can be obtained. The changes in the eccentricity take place with such extreme slowness, that by comparison with a cycle of such changes the period of 21,000 years which suffices for the rotation of the line of equinoxes relatively to the axis major will seem inconsiderable. Doubtless, when a period of high eccentricity has been reached, the orbit will remain in practically the same condition long enough to permit of two or even more than two passages of the line of equinoxes through that critical position which produces the maximum difference between the seasons.

Special attention must now be given to those epochs in the earth's history when these two agencies concurred to produce the greatest difference in length between summer and winter. It seems hardly possible to doubt that such epochs have been those of the Ice Ages. At first it might seem that a difference of 33 days between the lengths of the seasons would be hardly of sufficient significance to give rise to phenomena so colossal as those of the Ice Age. I think, however, we shall be able to show that the forces at our disposal are amply sufficient to account for the effects which have been observed.

I must here recall the fundamental theorem to which I have so often referred, which states that 63 per cent. of the total sun heat of the year on either hemisphere is received during summer, and only 37 per cent. is left with which to eke out the winter. Fortunately for the simplicity of our calculation, we have seen that these figures are independent both of the eccentricity of the orbit and of the position of the line of equinoxes. We are therefore entitled to apply these figures to those critical epochs in past time when, by a confluence of causes, the maximum difference in duration of seasons had been reached. There was therefore an epoch, or doubtless more than one, when the seasons were 199 and 166 days, and when the shares of sun heat received on each hemisphere during those seasons were 63 and 37 respectively. We may express the matter a little more clearly by describing more particularly the case of the Northern Hemisphere. There were epochs when the Northern Hemisphere had a summer of 199 days and a winter of 166 days; there were also epochs when in the same hemisphere the winter endured for the long period of 199 days, while the summer only lasted for 166. In each case, however, the figures 63 and 37 are to represent the proportional quantities of heat which that hemisphere received in summer and winter respectively. We have to suppose two cases, that in which the long season was the summer and the short season the winter, and that in which the long season is the winter and the short season the summer. The climatic conditions of these two cases are profoundly different. In the first place the long summer and the brief winter would certainly afford a much more uniform distribution of the sun's benefits than would be found in the opposite case. Seeing that 63 measures of heat come in summer and 37 in winter, it would seem equitable that the 63 measures should extend over the long season of 199 days, leaving the 37 measures to do the best they could for the brief winter of 166 days. But while the Northern Hemisphere was enjoying the beneficent climate which these figures indicate, the climatic condition of the Southern Hemisphere would be totally different. There, too, the seasons had the same lengths of 199 and 166 days respectively, but of course the summer in the Northern Hemisphere was the winter in the Southern; and consequently while the 63 measures of heat, which the Southern Hemisphere received, were all poured in during its brief summer of 166 days only, the remaining 37 were left to supply the protracted winter of 199 days.

In Fig. 4 the true shape of the earth's orbit is shown at a time of greatest eccentricity. The earth is, of course, represented on a monstrous scale, in order to distinguish the hemispheres. The Northern is glacial, and the Southern genial. In Fig. 5, which represents the state of things 10,500 years later, the Northern is genial, and the Southern is glacial.

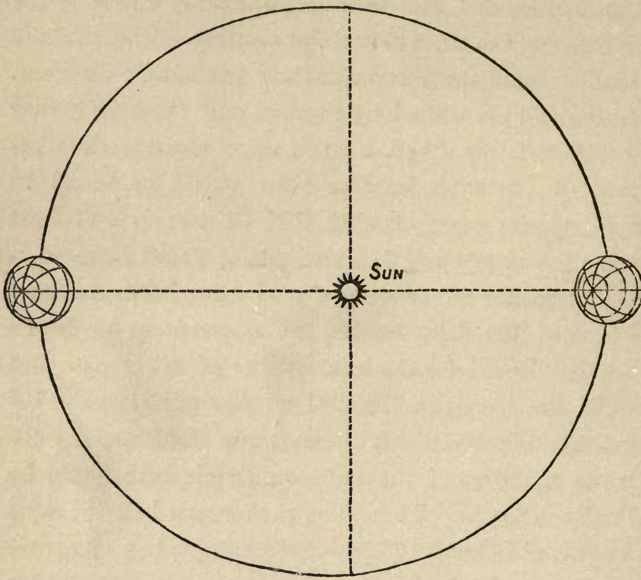

FIG. 4.—A GLACIAL NORTHERN HEMISPHERE.

There is another mode of expressing the same result which possesses some advantages. If the daily average receipt of heat from the sun on a hemisphere be taken as unity, then of course the receipt during the whole year will be represented by 365; this is not, however, imparted uniformly, for 229 of these units are contributed during summer and 136 during winter.

This exhibits in a rather instructive manner the extreme contrasts between the climates of the two hemispheres, that have occasionally arisen.

We express them as follows:

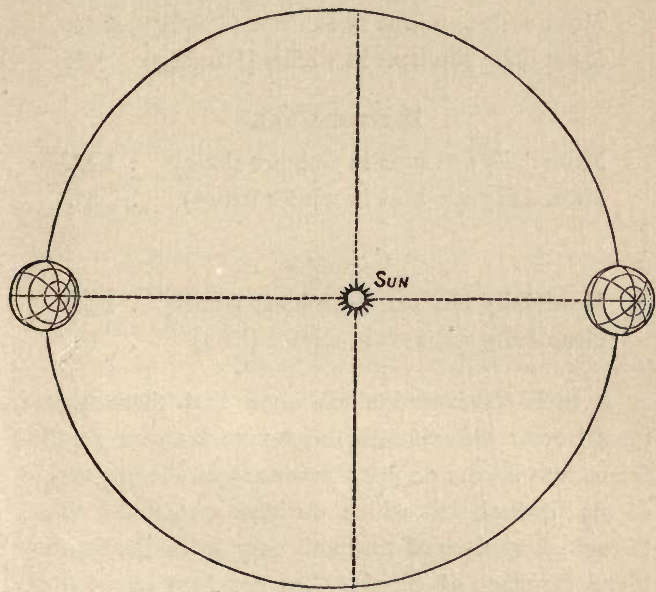

FIG. 5.—A GENIAL NORTHERN HEMISPHERE.

INTERGLACIAL.

229 heat measures spread over 199 days.

136 heat measures spread over 166 days.

GLACIAL.

229 heat measures spread over 166 days.

136 heat measures spread over 199 days.

From these figures we are enabled to deduce the average daily receipt of sun heat by each hemisphere under the several conditions as follows:

PRESENT (NORTHERN HEMISPHERE).

Mean daily sun heat in summer (186 days)	1·24.
Mean daily sun heat in winter (179 days)	·75.

INTERGLACIAL.

Mean daily sun heat in summer (long) .	1·16.
Mean daily sun heat in winter (short) .	·81.

GLACIAL.

Mean daily sun heat in summer (short) .	1·38.
Mean daily sun heat in winter (long) .	·68.

A little consideration will show that these figures must import wide climatic differences between the different seasons, for we must never forget the magnitude of the thermal unit which we have employed. What the actual measure of that unit may be in the conventional language of physics does not here concern us. To appraise its value it will be sufficient to allude to its effects. We have already pointed out how the heat received from the sun suffices to maintain our earth at a temperature which is 300, or more, degrees above that to which it would sink if the sun's heat were withdrawn. We are therefore provided with a notion of the value of our unit by the excess of temperature above that of space, at which the earth is maintained. Looked at in this way we can readily believe that a fall of one tenth in the supply of sun heat might correspond to quite an alarming fall in temperature. We can hardly pretend to express the range of the fall accurately, for a multitude of conditions are involved which are only imperfectly known to us. It will, however, be obvious that if a certain supply of sun heat is required to keep our earth at a temperature 300° above that to which it would otherwise drop, then a reduction of one tenth in the supply would involve a fall of many degrees in the temperature. The strict numerical proportion would of course indicate a fall of 30°, but we should certainly not be justified in supposing that this exact proportion would be observed.

It is useful to contrast the extreme conditions of our globe with the present condition. In the Northern Hemisphere, for example, we now have a summer of 186 days and a winter of 179 days. As the summer is seven days longer than the winter, we enjoy at the present moment what may be regarded as a faint approximation to an interglacial or genial period. In the Southern Hemisphere, on the other hand, the winter exceeds the summer, so that the tendency in that hemisphere is toward—but only a short way toward—a glacial epoch. At present, in the Northern Hemisphere, the mean daily receipt of sun heat during summer is to be represented by 1·24; in a glacial condition of the same hemisphere the mean daily receipt of heat through the short summer would be 1·38. Thus we see that the summer days at the height of a glacial period would be as much warmer than those of our present summers as the daily receipt of 14 per cent. of an additional heat unit would make them. Bearing in mind the magnitude of the heat unit which is involved, a unit sufficient, as we have so often said, to maintain a temperature 300°, or more, above that which would be otherwise maintained, it is obvious that an increase of 14 per cent. in sun heat must necessitate a large increase of temperature; the brief summer, therefore, in the glaciated hemisphere will be intensely hot, so far as direct solar radiation is concerned.

At present the mean daily receipt of heat in our Northern Hemisphere during winter is expressed by ·75; the corresponding figure during the glacial epoch would be ·68. It therefore follows that the mean daily receipt of heat during the long and dreary glacial winter will be 7 per cent. of a heat unit below our present average daily supply in the Northern Hemisphere during the same season. At the first glance it might appear that a mere decline of 7 per cent. in the sun heat received would not be very momentous from a climatic point of view, but this first impression will be modified when we consider two other factors in the question. In the first place, the winter was then 33 days longer than the summer, instead of being 7 days shorter, as it is at present. The effects of intense cold had, therefore, a longer time in which to accumulate, while the brevity of the succeeding summer would tend to impair its power of dissipating the ice and snow which gathered in the long winter. Then, too, we must remember in what units the 7 per cent. is expressed. A certain average daily supply of heat is continuously required to maintain our temperature at an elevation of at least 300° above the temperature of space; a decline in that supply to the extent of 7 per cent. must involve a considerable fall in the temperature which that heat was capable of sustaining, unless in so far as its effect may be neutralized by the operation of other agencies.

We are now in a position to describe the astronomical theory of the Ice Age. So long as the earth's orbit retains a form which is nearly circular there can be no extensive glaciation; the seasons must succeed each other according to the same laws that they observe at present. When, however, by the disturbing effect of the other planets the earth's orbit passes from the nearly circular to the elliptic shape (such a state of things is only attained after immense intervals of time), then it endures during a period which is long enough for several Ice Ages. But this is only the first condition; another astronomical adjustment must conspire with a high degree of eccentricity. When the line of equinoxes happens to be perpendicular to the axis major of the ellipse, we have the second necessary condition for the establishment of an Ice Age. Nor is there anything arbitrary in the assumption that the adaptation of the line of equinoxes to this critical position shall take place once, or more than once, during the continuance of a high degree of eccentricity in the orbit. The changes in the shape of the orbit require enormously longer periods of time than those which suffice for the revolution of the equinoxes. The changes in the eccentricity proceed with such extreme slowness that the ages during which the eccentricity remains in the vicinity of its maximum value are long enough to admit of more than a single revolution of the line of equinoxes. Indeed, it would seem to have happened not infrequently that several successive revolutions of the line of equinoxes with respect to the axis major have had time for their completion before the eccentricity had sufficiently declined to render glaciation impossible.

Let us suppose that the Northern Hemisphere is so placed that the summer it enjoys lasts for 166 days and the winter for 199 days. The Northern Hemisphere will then be exposed to a brief and intensely hot summer, during which the sun is at its least possible distance, and to a long and excessively cold winter, during which the sun is at its greatest possible distance. This is the condition required for the development of glaciation. During the rigors of the winter the ice and snow accumulate, while the succeeding brief summer is not able to thaw as much water as has been solidified during the winter. Thus the ice grows from year to year, and an ice-sheet is produced which extends far beyond the limits within which ice-sheets are at the present time confined. All this time the Southern Hemisphere enjoys a climatic condition widely different from that of the Northern. It has no doubt a summer and a winter, but the winter has been short, and its severity has been further mitigated by the circumstance that the earth was comparatively near the sun. The formation of ice and snow during winter must have been carried on on a very restricted scale, or, indeed, wholly prevented. On the other hand, the summer in this delightful climate would contain as great a number of days as it was possible for that season to possess, but the fierce heat of the sun would be abated from its average amount, because the sun during all that season would be placed at the greatest distance from the earth which it was possible to attain. The astronomical elements of the problem are so definite, and the necessary climatic changes that they involve seem so obvious, that on purely astronomical grounds alone we seem almost entitled to assert that the earth must have passed through a repetition, and many a repetition, of great climatic changes.

It would, however, be a mistake to suppose that extreme cold was the sole requisite for the formation of an Ice Age. That is certainly not the case, for a large supply of heat somewhere or other is also a necessary element in the production of an ice-sheet. For what is an ice-sheet but an accumulation of the snow which has fallen? That snow has of course come from the clouds in which the moisture which forms the snow was suspended as vapor. The supply of vapor to the atmosphere has to be continuously maintained in order to provide for the perennial showers of rain or falls of snow with which the clouds are charged. The moisture which is elevated to the upper regions of the air has, of course, been derived from the seas which cover this globe. As the sunbeams pour down on the wastes of sea they evaporate the water, which ascends in the form of invisible vapor. The extent to which this operation daily goes on is astounding when expressed in figures. The daily quantity of water which ascends in vapor from the surface of the oceans would, when condensed again, occupy a volume of some hundreds of cubic miles. Before a pound weight of ice can be manufactured for a glacier a pound weight of snow must have fallen; that pound weight of snow necessitates that the sun shall have raised a pound of water in the form of vapor from the surface of the ocean. We are now enabled to see how important a factor heat must have been even in the formation of the ice-sheet. Professor Tyndall has remarked that the heat which would be required to evaporate enough water to form a glacier would be sufficient to fuse and transform into glowing molten liquid a stream of cast iron five times as heavy as the glacier itself.

The astronomical theory of the Ice Age shows at once where to look for the heat which is so necessary to the accomplishment of glaciation. It is important to observe that even when the earth's orbit has its highest degree of eccentricity, and when the severity of an Ice

Age is at a maximum, the total quantity of heat which the earth receives during the year has not been lessened; indeed, it is somewhat greater than when the orbit was more nearly a circle. If, therefore, the glaciated hemisphere received during its winter a deficient supply of heat to which the glaciation owes its origin, the defect of heat upon this hemisphere will have to be compensated by a superabundance elsewhere. More favored regions of the globe will accordingly enjoy a more copious supply of sunbeams, and thus those volumes of aqueous vapor will be provided which, put in circulation by the winds, are deposited in the form of snow where the ice-sheets are growing.

It will thus be seen that the explanation we have offered of the Ice Age depends upon the consequences of an irregularity in the supply of heat from season to season, notwithstanding that the total amount remains unaltered. It can hardly be denied that such great irregularities in the supply as we have shown to be the consequences of a suitable combination of astronomical conditions, must correspond to great climatic changes. But it has been doubted whether these climatic changes will necessarily be the same as those required for the production of extreme glaciation. For instance, it has been contended that no Ice Age can be produced in the Northern Hemisphere if the total quantity of heat in that hemisphere received during the course of the year remains unchanged. At first sight it must be admitted that the view here taken is a plausible one, nor can it be denied that there are considerable difficulties connected with this aspect of the matter. A little attention may tend to lessen the difficulty. The formation of an ice-sheet is an operation of such magnitude that it is wholly impossible for it to arise as the product of a single season. We can not believe that the ice-sheet is manufactured afresh each winter and dissolved away during the ensuing summer; it must slowly grow from year to year, perhaps we might rather say from century to century, the net annual increase being determined by the excess of the ice produced during the winter over the ice melted during the ensuing summer. If a certain daily average of heat given uniformly be quite incompatible with the accumulation of ice, we have to explain how the ice-sheet does wax great when the same annual total of heat is given, but in such a way that each day in winter receives much less than its average and each day in summer much more than its average. Suppose a horse has a daily allowance of a stone of oats, which is sufficient to keep him in good health. The condition of that horse would be surely very seriously affected if he received a stone and a half for the first six months and but half a stone per day for the remainder of the year. Yet in this case, as in the former one, his daily average of a stone per diem has not been interfered with. In a similar way the irregularity in the supply of heat to the earth is capable of producing great climatic changes. No doubt if the earth had some absolutely perfect agency for storing up the excess of heat during the summer, and carrying it over to the next winter, it might be possible in that way so to equalize the climate that glaciation might not take place. Nature does not, however, provide any completely effective method for storing up the heat of summer; a great deal of it is radiated back again into space from the soil which it has heated, while much of the summer heat that falls on the surface of the ice and snow is reflected back again into space, and is not captured and stored away as heat would be, which was employed in melting the ice and snow. The sunbeams, in the brief and fiercely hot summer of the Glacial Period, failed to melt as much ice as had been accumulated during the preceding winter. Thus it was that the ice-sheet was permitted to grow from year to year until the stringency of the astronomical conditions became relaxed.

CHAPTER VI.

WHY THIS BOOK HAS BEEN WRITTEN.

It will be convenient at this stage to offer some explanation of the circumstances which led me to write this book. The most suitable method of doing so will be to give some account of my connection with the theory of the Ice Age.

Geology has always been a subject in which I have felt a special interest, chiefly on account of the many points of contact between that science and astronomy; it was therefore natural that I should have studied Dr. Croll's famous book on *Climate and Time.* I was greatly struck by this work when I first read it many years ago. Subsequent acquaintance with this volume, and also with his second work, *Climate and Cosmology*, has only increased my respect for the author's scientific sagacity, and my admiration for the patience and the skill with which he has collected and marshaled the evidence for the theory that he has urged so forcibly.

I was invited to deliver three scientific lectures before the Royal Institution of Great Britain in January, 1886. The Astronomical theory of the Ice Age seemed to me to offer a suitable subject, and as the theory had specially engaged my attention already, I accordingly chose it. Thereupon I commenced diligent preparation for my work, and I made a special examination of the astronomical doctrine on which the theory is founded. It soon appeared that the astronomical part of the subject depended mainly upon the investigation of the following problem: How much of the annual sun heat does a single hemisphere of the earth receive in summer, and how much does it receive in winter? I worked this out by the calculation which is given in the Appendix, and I discovered the law of distribution of sun heat on a hemisphere between the two seasons into which the year is divided by the equinoxes. This shed much light on the subject. I felt confident that the Astronomical theory gave the true solution to the Ice Age, and my lectures were duly delivered at the Royal Institution.

A few months later I delivered two lectures on the same subject before the Royal Dublin Society. It was thought desirable by some of my friends to have a more ample discussion of the mathematical part of the subject than would have been suitable for my lectures, which were addressed to a general audience. It was in compliance with this wish that I read a short paper before the Royal Irish Academy on May 24, 1886, entitled, *Note on the Astronomical Theory of the Great Ice Age.* In this I enunciated and proved that law of the distribution of sun heat between the two seasons which I have already referred to as the cardinal feature of this little book.

At the time I wrote the paper I merely desired to bring the matter prominently forward for discussion; I did not pretend to put forward any novelty, except, perhaps, in the manner in which the subject was treated. I thought that the law as I expressed it would be a compendious method of conveying what must have been familiar to those who had given any special attention to the subject. I may mention that I was desirous of diffusing among my scientific friends an interest in the doctrine, and I thought that a special method of calculating the astronomical part of the subject would conduce to that end. There, probably, my connection with the question would have terminated had it not been for something of which I afterward became aware. No doubt I had made out for myself and for my own information the law of the distribution of heat between the two seasons, but every one who is engaged in scientific work knows that matters like this are discovered over and over again by persons working independently at the same subject. It is therefore rash to claim novelty in such a matter. At this moment I think it possible that the law, or what is equivalent to it, may have been discovered and perhaps even published before; I have, however, never been able to meet with any account of it. I have not even observed in any of the writers with whom I am acquainted any consciousness of the existence of such a law. I confess that this has not a little surprised me. The law is so pregnant with significance that the theory of the Ice Age can not indeed be rightly understood unless by those who are acquainted with the facts to which it gives expression. It seems, however, certain that the true principle of the distribution of heat between the seasons is not generally known, if known at all; it is therefore the more necessary that it should be pressed on the consideration of those who have paid special attention to the connection between terrestrial climate and the shape of the earth's orbit.

I must, however, go farther than this. Not only did I find that the true law had been overlooked, but it became apparent that sometimes another law had been adopted which was absolutely incorrect. I found, furthermore, that the Astronomical theory of the Ice Age as ordinarily stated was contaminated with absolute blunders in the simple mathematical questions which are involved. When the true law of the distribution of heat between the seasons is introduced, it places the astronomical doctrine as to the cause of the Ice Age in an impregnable position. It appeared to me that this point had not been properly dealt with. The more reflection I gave to the subject, the more important did it seem, that the astronomical side of the question should at all events be stated with whatever mathematical accuracy it possessed, and hence it was that I conceived the idea of writing this book.

No one can feel a warmer admiration than I do for the splendid talents displayed by Sir John Herschel.

As an all-round astronomer he seems never to have had a rival. He was equally successful in observing with his telescope, in performing abstruse mathematical calculations, or in describing his discoveries in a style now regarded as classical. In the whole literature of astronomical research there is not a nobler work than that grand volume in which Sir John Herschel records the discoveries that he made at the Cape of Good Hope. A striking illustration of the great astronomer's powers as an expounder is exhibited in his volume *The Outlines of Astronomy*, which every one with a taste for science cherishes in a favored corner of his library.

In this book we find a remarkable paragraph, in which Herschel sets forth the relations between the changes in climates on the earth and the corresponding changes in the eccentricity of the earth's orbit. It runs as follows; I quote from the edition of 1875 p. 233:

"In what regards the comfort of a climate and the character of its vegetation the intensity of the summer is more naturally estimated by the temperature of its hottest day and that of a winter by its sharpest frosts than by the mere duration of those seasons and their total amount of heat. Supposing the eccentricity of the earth's orbit were very much greater than it actually is, the position of its perihelion remaining the same, it is evident that the characters of the seasons in the two hemispheres would be strongly contrasted. In the Northern we should have a short but very mild winter with a long but very cold summer, i. e., an approach to perpetual spring, while the Southern Hemisphere would be inconvenienced, and might be rendered uninhabitable, by the fierce extremes caused by concentrating *half* the annual supply of heat into a summer of very short duration, and spreading *the other half* over a long and dreary winter, sharpened to an intolerable intensity of frost when at its climax by the much greater remoteness of the sun."

I have italicized certain words in this passage which have unfortunately been the means of diffusing an entirely erroneous impression. Herschel has always been understood in this passage to say that at a time of maximum eccentricity, when the difference between the lengths of the seasons has attained a considerable value, there would be a difference in the climate, because 50 per cent. of the total heat of the hemisphere was poured in during the short season, while the remaining 50 had to be eked out over the long season. Indeed, his words seem to admit of no other interpretation. It is somewhat remarkable that Herschel has made a considerable error in this critical subject. It must be remembered that as the point in question is purely a mathematical one, there can be no room for doubt. He states that the heat is equally divided between the two seasons, and he considers that even in this case the difference between their lengths would necessitate a profound climatic disturbance. If, however, we employ the true law of the distribution of heat between the seasons we can correct the inaccuracy, and write the passage as, of course, Herschel would have done had his attention been sufficiently given to the matter. Every mathematician who will study the Appendix to this book will agree with me that the latter part of Herschel's paragraph should have read as follows:

"In the Northern we should have a short but very mild winter with a long but very cool summer, i. e., an approach to perpetual spring; while the Southern Hemisphere would be inconvenienced and might be rendered uninhabitable by the fierce extremes caused by concentrating *sixty-three per cent.* of the annual supply of heat into a summer of very short duration, and spreading the *remaining thirty-seven per cent.* over a long and dreary winter sharpened to an intolerable intensity of frost when at its climax by the much greater remoteness of the sun."

It thus appears that the accurate law of the distribution of heat had escaped the attention of Herschel; it seemed, therefore, not impossible that it might also have been missed by other writers. Indeed, on such a matter it was not unnatural that the words of Herschel should have been adopted without any very critical scrutiny. I examined Croll's books carefully on this point. I need hardly repeat here the extent of my indebtedness to Croll, and how cordially I add my testimony to the value of his work. I must, however, say that after close study of his writings I have been obliged to come to the conclusion that he also has not made use of the true law of distribution of heat between the seasons. So far as I can gather from the various allusions to the astronomical elements of the problem in his writings, it would seem as if he entertained the same view as that which is incorrectly set down in *The Outlines of Astronomy.* I have at all events failed to find in his most famous book, *Climate and Time*, or in his later work, *Climate and Cosmology*, any use made of the law that under all circumstances and on either hemisphere 63 per cent. of the total heat of the year is received during summer, so that only the remaining 37 per cent. is left for winter.

And yet this law is essential to the right understanding of the subject. It is impossible to form a just appreciation of the connection between the eccentricity of the earth's orbit and the climatic phenomena of the globe unless under the guidance of the principle which underlies the law we have so often mentioned; it must be constantly borne in mind, and regarded as an essential element which astronomy contributes to the problem.

It always seems to me that Dr. Croll would have been enabled to do his theory much more justice if he had been in possession of this law. It would surely have made a material difference in his reasoning if he had been aware that the total heat received in the course of a summer, whether long or short, was nearly twice as much as the total heat received in any winter, whether short or long. In fact, Dr. Croll's task would have been greatly facilitated, for the agencies at his disposal would have been of greatly increased efficiency. I felt desirous to see what the Astronomical theory of the Ice Age would look like when the true law of the distribution of heat between the seasons was employed. I found that the evidence of the origin of the Ice Age from astronomical causes was greatly strengthened, and I have written this little book in order to have an opportunity of expounding the matter.

As I have been obliged to point out the necessity for a correction in a passage in the *Outlines of Astronomy*, I will take the opportunity of suggesting how it probably happened that a statement which has been the source of so much misconception came to be made. It is certainly true that during the summer in one hemisphere the heat received *on the whole earth* is equal to the heat received *on the whole earth* during the ensuing winter on the same hemisphere It seems likely that the assertion in the *Outlines of Astronomy* was somewhat hastily set down in the belief that it was merely another way of expressing the remarkable proposition just given. A little closer reflection will, however, show that the two statements are not at all equivalent.

The doctrine at which we have arrived is so important to the theory of the Ice Age, that I feel tempted to suggest it as a very ready test to see whether any one who professes to discuss the subject has correctly perceived the astronomical bearing of the case. The essence of the subject is mainly comprised in two fixed quantities, represented by the numbers 63 and 37 respectively. No one can understand the Astronomical theory of the Ice Age without at once recognizing their significance. They denote the percentages of the total heat of the year received on one hemisphere during summer and winter respectively; they derive their importance from their constancy. They would remain the same however the dimensions of the orbit be altered, however its eccentricity be altered, or in whatever direction the plane of the earth's equator may intersect the plane of the earth's revolution around the sun. These numbers are both functions of but a single element, which is the obliquity of the ecliptic. As this fluctuates but little, at least within the periods that are required for recent Ice Ages, the numbers we have given are regarded as sensibly constant throughout every phase through which the earth's orbit has passed within glacial times. The effect of eccentricity, though powerless so far as the quantities expressed by these numbers are concerned, is shown by the alterations in the lengths of the seasons. We may have a short summer and a long winter, or a short winter and a long summer. Be the summer, however, long or short on the Northern Hemisphere, that hemisphere will invariably receive 63 per cent. of its total sun heat for the year during the summer, and 37 per cent. during the winter. Obviously the most beneficial arrangement will be that of a long summer and a short winter, for the extremes of climate will be thus moderated. The greatest difference in the lengths of the seasons will be when one is 199 days and the other 166 days; one of these is to be the summer and the other to be the winter.

Let us suppose that a gentleman whom we shall call A has a salary of £100 a year, which is paid in two installments of £63 and £37 respectively. One of these sums is understood to be payment for the summer portion of the year, leaving the other for the winter. Let us now make a calculation to see how he will fare under varied circumstances. We may first suppose that there is the longest possible summer and the shortest possible winter. The summer lasts for 199 days, during which a sum of £63 furnishes to him the means of support. His daily allowance during this season would of course be found by dividing 199 into £63, by which we obtain 6*s*. 4*d*. In the following winter he receives only £37; however, this has not to last more than 166 days, so that his average receipt per diem would be 4*s*. 5½*d*. The difference between the mean daily summer income and the mean daily winter income is, therefore, not more than 1*s*. 10½*d*. Under these circumstances A enjoys a fairly beneficent arrangement. To take another case, let us suppose that the summer is the short season, leaving the winter to be the long one. A is then lavishly provided for during the brief summer of 166 days, in which he has to spend £63. His daily average would then be 7*s*. 7*d*. This extravagance will leave him but a very scanty allowance during the winter. He has in that long and dreary season to eke out £37 for 199 days, during which his daily allowance will be but 3*s.* 8½*d.* His condition is a very unhappy one; he is in a glacial epoch. Let us now write our account of this gentleman's affairs in a tabular form:

	Summer	Winter	
A's daily income . .	6*s.* 4*d.*	4*s.* 5½*d.*	genial
" " . .	7*s.* 7*d.*	3*s.* 8½*d.*	glacial

It needs only a glance at these figures to show that there will be a considerable difference in the comforts enjoyed in the two cases. The most appropriate method for ministering to A's daily wants would obviously be that by which the income may be equally distributed over the year; and if perfect uniformity can not be obtained, then the nearer approximation to equality the better. Under the condition which we have here marked as genial, no doubt A enjoys more in summer than he has in winter, but the difference between the daily allowance in the two seasons is far greater in the second case than in the first. In fact, he can only devote 3*s.* 8½*d.* to his maintainence per diem during the long and severe winter, which is less than half that which he receives during the summer—7*s.* 7*d.* Now, to a certain extent this will illustrate the condition of our earth as regards the daily receipt of heat from the sun. When the eccentricity is at its greatest, and when the inequality of the seasons is at a maximum, then the Northern and the Southern Hemispheres will each be represented by one of the two cases just referred to. In the Northern Hemisphere, for instance, the daily receipt of heat during summer may not be half as much again as the daily heat of winter, and then the genial conditions prevail. In the Southern Hemisphere, at the same time, the average daily receipt of heat in summer will be more than double that in winter, and the glacial conditions will prevail. Perhaps the illustration of an income of £100 a year hardly conveys an adequate conception of the disparity between the glacial and genial conditions. By taking a somewhat smaller sum we may easily conceive a case in which, while the same proportions were observed, the lowest sum on which life could be supported should lie between the winter allowance in genial and glacial times respectively. Under such circumstances, while the income would be sufficient for mere maintenance so long as the genial division of seasons was observed, the same income would prove insufficient for the maintenance of life when the seasons were divided, as in a glacial epoch. A prudent person would, however, have saved up a little of the abundance of summer to help him over the winter. Something of this kind does happen on our globe in the case we are trying to illustrate; the waters on the earth store up a portion of the redundant supplies of heat in summer, and employ it to mitigate the rigors of the ensuing winter.

There is, however, another way in which the horrors of an Ice Age are to some extent lessened. At the time when one hemisphere is glaciated the opposite hemisphere is in a genial condition, and by the agency of winds and of ocean currents the abundant warmth of the fortunate hemisphere is conveyed to the succor of the glaciated districts. Even the very snowfalls themselves, in so far as they arise from vapor conveyed from the genial hemisphere, are vehicles for the conveyance of vast quantities of latent heat, which is liberated on the congelation of the vapor. There can not be a doubt, if the two hemispheres were completely isolated by an impassable barrier around the Equator, so that no winds could cross from one hemisphere to the other, or no waters traverse the dividing line, that then the distinction between a glacial epoch and a genial epoch would be much more strongly accentuated. Suppose that a trough is divided into two parts by a movable partition, if one of the parts be filled with hot water and the other with cold water it is obvious that if the partition be withdrawn the two waters will speedily blend, the lighter hot water will flow over the adjacent cold water, and the cold water will penetrate beneath the hot water, and an equilibrium of temperature will be more speedily attained. Probably a similar interchange of heated water for cooled water takes place on an enormous scale at the Equator during the time when one hemisphere is glaciated and the other is in a genial state. During the glacial winter the daily receipt of heat is only ·68, while in the genial summer enjoyed simultaneously on the opposite hemisphere the daily receipt of heat is 1·16. The difference between them is ·48, and we must always remember that the unit in which these quantities are expressed is a very large one, sufficiently large, indeed, to express the daily supply of heat that must be communicated to the earth to prevent it from sinking down over 300 degrees in temperature. A tremendous export of heat must take place all through the summer from the genial hemisphere, thus alleviating in some degree the wants of the long winter in the glaciated hemisphere.

To return to our illustration, let us suppose that the gentleman A has a brother B in the Southern Hemisphere who receives the same salary, and whose emoluments are payable to him in the same manner, viz., a sum of £63 for the summer, and of £37 during the winter. At a time when the difference between the lengths of the seasons is a maximum, one of the hemispheres is glacial and the other is genial. No doubt the most beneficial arrangement would be one by which A would receive aid from B during the dreary glacial winter, and B will be able to afford this because he has 6*s.* 4*d.* per diem, while A will sadly want help, having only 3*s.* 8½*d.* Thus, by contributions from the opposite hemisphere the sufferings of glaciation may be somewhat lessened. Of course, when the next great transformation has taken place, by which the glaciated hemisphere and the genial hemisphere change places, it will be A's turn to afford succor to B.

Thus we learn that there are two causes by which the severity of a glaciation is somewhat modified.

There is, first, the actual storage of some of the copious heat of summer in the glaciated hemisphere itself, to be doled out again during winter; there is, secondly, the contributions of heat from the opposite hemisphere, which may be conveyed *via* air or *via* water across the Equator into the glaciated regions.

I now proceed to explain the way in which we are able to form some conception of the actual quantitative effect on climate which may be expected to arise from the fluctuations in the eccentricity of the earth's orbit. The subject presents many difficulties, and I naturally feel some diffidence in discussing it. I think, however, that the views which I shall here give seem hardly open to much exception. At all events, I do not think they can be said to err on the side of attributing too great a significance to the climatic consequences of increased eccentricity.

Let us begin by considering the present state of our globe. We shall speak more particularly of the Northern Hemisphere, because the facts with reference to it are, of course, more accurately known than are those of the Southern Hemisphere. Under existing circumstances the lengths of the two seasons are respectively a summer of 186 days and a winter of 179 days. At present, as at all other times, 63 per cent. of the total annual heat on the hemisphere is imparted during the summer, and but 37 per cent. is left for the winter; there is, therefore, a wide difference between the daily receipt of heat during the two seasons. If, as before, we denote by unity the average amount per hemisphere, then that during summer will be 1·24, and during winter 0·75.

It is to this inequality that we are to attribute the familiar difference between the mean temperature of summer and that of winter, and our first impression may well be one of surprise when we notice that the contrast in warmth between the two seasons is not a much larger one than our experience has shown it to be. It will be observed that the difference between the figures we have just given amounts to 0·49, that is, almost to half the unit of heat which we have chosen. Remembering what a considerable thermal magnitude we have chosen as the unit of heat we might at first expect that the difference between the temperature of summer and the temperature of winter should be much larger than it is. For the unit of heat is that which on the average sustains the earth at the temperature which it has above the temperature of space. Since, then, the unit of heat is competent to sustain a temperature which is to be measured by some hundreds of degrees, it might not unreasonably be expected that, when half a unit a day is received in summer above the daily allowance for winter, the range of temperature between a summer's day and a winter's day should also require to be expressed by three figures.

Probably this would be the case were it not for the equalizing tendency of the agents to which we have already referred. These agents exercise their beneficent influence with especial emphasis on the British Islands. The consequence is that on our Western shores the mean difference between the temperature of the summer and the temperature of winter is about 20°. In the interiors of the great continents the climatic effects of the ocean are experienced less, and consequently the range of temperature between summer and winter rises. In the middle of North America, at the same latitudes as the British Islands, the range between summer and winter is about 60°. In Eastern Asia, still in the same latitudes, the range rises to 80°, while a little to the north, in Siberia, the range rises to 100°. Thus we see that, when the influences of mitigating agents are sufficiently lessened, the range between summer and winter attains a magnitude approaching to the theoretical result that might be expected from the fact that the daily receipt of heat was almost half a unit less in winter than in summer.

Mr. Scott, in his well-known *Elementary Meteorology*, tells us that at Yakutsk (Siberia) the temperature in the hottest month is 65·8°, while it sinks to 44·9° below zero in the coldest. Here the range is over 100°; but it will of course be observed that these figures refer, not to the mean temperature of summer and winter, but to the maximum and minimum temperatures respectively.

Let me here specially ask the reader's attention to the line of argument that is to be followed. I shall take the case of the British Islands, and endeavor, so far as may be, to form some estimate of the extent of the climatic changes that could be there induced by such a combination of astronomical conditions as gives rise to an Ice Age.

At the present moment the difference between the daily receipt of heat during the summer and during the winter is on the average ·49 of the unit. It is this difference which is the cause of the disparity between summer and winter temperatures. At present this disparity is in the British Islands at so low a value as 20°. The mitigating causes act so vigorously in Great Britain, owing to the peculiar circumstances of its geographical position, that ·49 of the unit only produces the trifling effect of 20°; nothing can, however, be more certain than that these two quantities stand in such a relation to each other that, if one of them be altered, the other will also alter, or, as the mathematician would say, the mean range of temperature must be a function of the mean difference between the summer and winter daily receipts of heat. To avoid misapprehension, I should and that of course there are many constant elements necessarily involved, which depend on the locality.

At the time of high eccentricity, when the summer only lasted for 166 days and the winter for 199, the daily unit of heat received during the hot and brief summer is 1·38, while the daily average heat received through the long and dreary winter is only ·68. The difference between the two seasons is thus on the average ·70 of a unit. By the method of treatment that we are now adopting, we avoid any embarrassing considerations as to the absolute temperatures. It is sufficient for us to note that in each locality the excess of the mean summer temperature over the mean winter temperature may not unreasonably be taken to be proportional to the excess of the daily heat received in summer above the daily heat received in winter. If this excess be altered in any ratio, the range of temperature will be increased in a ratio which is about the same. We have seen that certain ranges are appropriate to a heat difference of ·49. If the heat difference become ·70, the range may be expected to be increased in a similar proportion; in other words, the localities which now show a range of 20° will show a range of 28°. In the same case the countries which have at present a mean range between summer and winter of 40° would acquire a range of 57° in a glacial period, while in the bleak regions which now have a range of 60° we should find a range of 85° during the prevalence of glaciation.

These changes are quite large enough to imply profound differences in the climatic condition. It is to be observed that, generally speaking, the coldest places are those of the greatest mean annual range. We are therefore entitled to infer that the effect of such a change in the eccentricity as we have supposed, would be to increase the range, lower the temperature of the hemisphere, and thus induce the glacial period.

The contrast between the conditions of the genial hemisphere and of the glaciated hemisphere can also be estimated with some precision by the same line of reasoning. If at a time of maximum eccentricity the summer has the greatest possible duration and the winter the shortest, the daily average receipt of heat in the summer is 1·16, and the daily average for winter is ·81. The difference between these quantities is ·35. If therefore a difference in the daily receipt of heat amounting to ·49 corresponds to a range of temperature of 20°, it ought to follow that in the genial period the range should be reduced in the ratio of ·35 to ·49—that is to say, the range of 20° is reduced to 14°. We are thus entitled to infer that during a Genial Age the mean range in the British Islands would be 14°, while during a Glacial Age the mean range would be 28°.

Of course we may obtain similar results from other ranges. Suppose, for example, a country which has at present a range of 60° between its mean summer and mean winter temperature. This is produced, of course, by the fact that the daily average receipt of heat in summer is ·49 of a unit greater than in winter. This fact modified by local circumstances causes in the region under consideration a range of 60°. But now suppose that the quantity which is at present ·49 were raised, as it would be in a glacial period, to ·70, and that the other circumstances affecting the question (being mainly geographical) remain substantially the same: we should then be entitled to assume that the range between the mean temperature of summer and the mean temperature of winter would be raised in the same proportion

—that is, from 60° to 85°. On the other hand, during a genial period, when the quantity which is now ·49 drops to ·35, there is a proportional fall in the range from 60° to 43°.

This calculation brings out the significant fact that in a genial period the range in any locality would seem to be merely one half of what it was when the glaciation reigned in that hemisphere. Of course it will be understood that the presence of an ice-sheet must largely affect any such statements. If we remember that when one hemisphere is glaciated the other is in a genial state, the contrast between the two seasons is emphasized in a very marked way. It may also be noticed that we generally find the mean annual temperature is high in places where the range of temperature between summer and winter is small. A great range is generally a concomitant of a low mean annual temperature.

I have been unable to perceive the validity of the arguments by which Dr. Croll strives to show that a great ocean current like the Gulf Stream must be actually diverted from one hemisphere to the other, as a consequence of the transference of the glaciation from one hemisphere to the opposite. I can not think this is likely, nor does it seem necessary for the explanation of the Ice Age. Once the true significance of the astronomical facts has been realized, it is apparent that, leaving the other agents much as they are at present, the alteration in the range of temperature will be amply sufficient for even extreme changes in climate.

At the present time the range in the Southern Hemisphere between the mean summer temperature and the mean winter temperature appears to be less than in the Northern Hemisphere. It must be admitted that at the first glance this is a little disappointing in view of the theory now put forward. As the seasons are at this time 179 days and 186 days, and as in the Southern Hemisphere the winter lasts for the longer of these periods and the summer for the shorter, it might seem that at present there should be to a certain extent an approach to a glacial period in the Southern Hemisphere. We should accordingly have expected that the ranges there were greater than the ranges in corresponding latitudes in the Northern Hemisphere. The opposite, however, is the case, as is pointed out in Scott's *Elementary Meteorology*, to which I have already referred. No doubt the explanation of the discrepancy is to be found in the far greater extent of ocean-covered surface in the Southern Hemisphere than in the Northern. The sunbeams which fall on the sea are retained sufficiently long to enable the redundant heat of summer to contribute effectively to the amelioration of the winter.

I hope the position that I have here taken with respect to Dr. Croll's views may not be misunderstood. Like him, I thoroughly believe in the Astronomical theory, but it has a far greater claim on our belief than that which previous writers seem to have imagined; in fact, Dr. Croll seems not to have been really aware of the full strength of the argument from astronomy. He appears, in common with many others, to have been influenced by Herschel's unfortunate inadvertence in the statement quoted above. Even on the supposition—the erroneous supposition as we now know it to be,—of equal heats in the two seasons on the same hemisphere, it was considered by the advocates of the Astronomical theory that the inequality in duration of the two seasons would be sufficient, directly or indirectly, to originate some climatic changes. However, we now know that the total heat in one of the seasons is nearly double that in the other; and this being so, see what a powerful lever is afforded for the production of climatic effects. If the long season be the summer, and the short season the winter, then the double supply of heat is distributed over the long period, and the single supply over the short one. This has a beneficent effect on climate, and a Genial Age is the consequence. If, on the other hand, the double supply of heat be poured in like a torrent during the short season, while the single supply of heat is constrained to do duty over the long season, then an intolerable climate is the result. The total quantity of heat received on the hemisphere in the course of a year is no doubt the same in each case, but its unsuitable distribution bespeaks a climate of appalling severity—an Ice Age, in fact.

There is another point of view from which it will be seen that Dr. Croll's theory is much stronger when exhibited in the amended form rendered necessary by the law of distribution of heat between the two seasons.

If the heat in summer and the heat in winter were equal, then there would be only the inequality in the lengths of the seasons to be taken into account in estimating the agencies of glaciation. On the supposition that the receipts of heat during the two seasons were equal, we find that at a time of glaciation the daily influx of heat during the long and cold winter would be ·92, while the daily receipt of heat during the shorter glacial summer would be about 1·10. In making these calculations we have assumed that the heat was uniformly received throughout the summer, and uniformly received throughout the winter. According to this view the climate is glacial when the summer is short and the winter is long, and genial when the summer is long and the winter short. In any case, however, the greatest contrast between the mean daily influx of heat in summer and the mean daily influx of heat in winter are to be represented by the figures 1·10 and ·92 respectively. The difference between these two is ·18 of our heat unit. This shows in a striking manner what a wholly inadequate presentation the Astronomical theory received, when expounded, under the belief that the total heat of summer was equal to the total heat of winter. Were this the case, the utmost difference between an average summer day's heat and an average winter day's heat could be only ·18 of a unit, while, as we have already seen, when accurate data are employed, the maximum difference between an average summer day's heat and an average winter day's heat may amount to ·70. The difference between these two numbers amounts to more than half our unit of heat, and when we remember what that unit of heat implies, it shows how necessary it is that the facts should be properly stated. I venture to commend the points raised in this chapter to the careful consideration of the numerous workers at the fascinating subject of the monuments left by ancient ice.

CHAPTER VII.

HOW THE ASTRONOMICAL THEORY IS CORROBORATED.

It is of the essence of the Astronomical theory that a glacial epoch in one hemisphere shall be accompanied by a genial epoch in the other, and that after certain thousands of years the climatic conditions of the two hemispheres shall become interchanged—that the ice shall leave the hemisphere desolated, and fly to the other, while the regions it has abandoned shall become clothed with luxuriant vegetation characteristic of a genial epoch. Such fluctuations seem to have occurred again and again; in fact, that they do so is a necessary consequence of the Astronomical theory of the Ice Age. The oscillations of glaciation from one hemisphere of the earth to the other is a phenomenon of the most singular interest, and it is natural that we should desire to study it from every point of view. The Astronomical theory does not give us many of the details which we should like to know. It tells us, however, with reasonable approximation the periodic time of these changes. From the time of the climax of an Ice Age in one hemisphere to the time when, having left that hemisphere, it has become established in the opposite one, has abandoned it, has returned to its original home and has again regained its climax, the interval is about 21,000 years. This period is not affected with the uncertainty that attaches to certain other attempts at the chronology of the Ice Ages. It depends on two astronomical constants, and of these the first is the period of the precession of the equinoxes. If the earth's orbit retained a constant position in its plane, then we could assert, with every confidence, that the interval from one phase of an Ice Age to the return of the same phase in the same hemisphere would be the period of 25,694 years. However, the earth's orbit does not always remain in the same situation, for the attractions of the planets cause the elements of the orbit of the earth to be more or less variable. The position of the axis of the earth's orbit forms no exception to this law; it has a slow motion in the plane of the orbit, which can be determined with sufficient accuracy. Its effects become blended with those of the precession of the equinoxes, thus producing a net movement of the axis relatively to the equinoxes of 1° 42·6′ every century. Thus we obtain for the period of the changes a term of about 21,000 years. It should be distinctly understood that neither in this place nor in any other do I make any attempt to estimate either the date of the last glacial epoch that desolated the earth, or the date at which the next may be expected. It is true that such estimates have been formed, but they depend upon formulæ which can hardly be relied on for such an extreme application as is demanded of them. What I now desire to convey is, that when, after the lapse of gigantic periods, a series of conditions suitable to glaciation have supervened, then, for so long as those conditions remain fulfilled, the ice-cap oscillates between one hemisphere and the other with the interval of 21,000 years that we have just determined.

To Dr. Croll must be ascribed the credit of having pointed out that the remarkable succession of Ice Ages which we have here indicated was a necessary consequence of the Astronomical theory of their origin. At first it was regarded as a little startling that a demand should be made not for one Ice Age nor for two, but for such a series, or rather for such a series of clusters of associated Ice Ages as those which the Astronomical theory seemed to require. It was also regarded as somewhat startling that the marvelous oscillation of glaciation from hemisphere to hemisphere should have taken place, as it most assuredly must have done, from the consequences of the relations of the earth to other bodies in the solar system. It was therefore natural that an appeal should be made to the facts of geology to see whether they could offer any confirmation of phenomena so extraordinary. Geology affords us distinct traces of the repetition of glacial phenomena, but it could hardly be expected that the facts of that science could throw much direct light on chronological matters as to the order of succession of Ice Ages in one hemisphere and the other. We might, no doubt, find—indeed we actually do find—traces of an Ice Age in the Southern Hemisphere just as we find them in the Northern; but though the rocks have been engraved with unmistakable characters by glaciers and ice-sheets, yet these inscriptions do not tell quite so much as we should like to know. They assure us, no doubt, that Ice Ages have occurred in both hemispheres, but they leave us uninformed as to whether these Ice Ages were consecutive, or as to whether they were concurrent. Now this is not a mere matter of ordinary significance, as it involves an absolutely vital point in the Astronomical theory of the Ice Age. So much so is this the case, that if it could be shown that the Ice Ages in the two hemispheres were concurrent, the Astronomical doctrine would have to be forthwith abandoned. Of course, there is no chance of such a contingency arising, and I merely enunciate it to show the significance of the doctrine, that the Ice Ages in the opposite hemispheres were not concurrent but were consecutive; in fact, we may feel convinced on astronomical grounds alone that this must have been the actual state of things.

No matter how confident we may feel as regards an important result arrived at by one line of reasoning, it must necessarily be of interest to note the confirmation of that fact by reasoning of a wholly different character; especially would this be the case when the evidence in the second case was elicited from a distinct branch of science. There is no more interesting illustration of the principle just mentioned than the fact that botany affords a striking confirmation of the Astronomical theory of the Ice Age.

When the tourist climbs the Alps in early summer he finds that a charming flora claims a share of that admiration which he so freely bestows on the glorious objects around him. He is struck by the contrast between the flowers on the mountains and the flowers that bloom in the valleys beneath. Nor is it only in the Alps that the peculiar characteristics of a mountain flora will arrest the attention of the tourist. The flora on the summits of the Pyrenees and on all other great mountains are of special types, differing in important respects from the plants in the adjacent lowlands.

In our own islands the summits of lofty mountains offer the conditions congenial to remarkable plants that find no habitat on the plains. In the New World, also, the summits of mountains nourish plants differing widely from those that grow at their feet. Indeed, a similar statement may be made about every continent. The labors of botanists have demonstrated that the vegetation on the summits of lofty mountains has often certain features in common, even though those mountains may be situated in different continents and separated by thousands of miles of intervening ocean. In fact, it is usual to employ the common term Alpine to indicate the vegetation characteristic of mountain summits. There are some interesting pages on this subject in the *Origin of Species.* I shall here endeavor to summarize, from what Darwin says, the facts which bear on the subject of this little volume.

It is surely remarkable to find that the summits both of the Alps and of the Pyrenees are the abode of plants which also thrive in the bleak and dreary extreme North of Europe. In the intervening low countries these plants do not occur. How does it come to pass, that where the conditions congenial to these plants are found, there those plants grow, notwithstanding that they are separated by hundreds of miles from the similar flora in other regions? No one will believe that they were independently created in many widely separated localities; and therefore some other explanation must be sought.

There are kindred facts of a still more striking character. The plants which thrive on the summits of the White Mountains in the United States are the same as those in Labrador, and we have the authority of Asa Gray for the assertion that such plants are also closely related to others on the loftiest mountains of Europe.

This remarkable phenomenon in the distribution of plants can be satisfactorily accounted for only as a consequence of the existence of the Ice Age. To illustrate the argument, it will be convenient to follow the method of Darwin, and trace some of the consequences of the advent of an Ice Age, and then its gradual disappearance.

In the normal condition of the Northern Hemisphere, the characteristic but scanty Arctic flora lends what verdure it may to the solitudes in the neighborhood of the Pole. The severity of the climate, which would prove fatal to the plants adapted to an abode in Southern and more genial climes, is necessary to the well-being of these Arctic plants. At present the temperate lowlands of the earth are uninhabitable by such organisms; they would perish there just as the plants of our temperate regions would at the North Pole. With the advent of a glacial period the temperate regions of the globe undergo such a mutation of climate, that the inhabitants, both animal and vegetable, which now thrive there would gradually be driven to southern regions in search of the warmth which was indispensable to their existence. The same climatic changes would, however, offer an inducement to the Arctic plants to visit those regions at present temperate, but which, by the change of climate, became adapted to a cold-loving flora. The vegetation which, under normal circumstances, grew on the summits of mountains in the temperate regions would, with the approach of a glacial period, descend the mountain sides and commingle in the plains with the productions of the Arctic regions which had migrated southward. It is also to be noticed that the present Arctic flora appears to be of a similar character all round the Pole. Consequently, as the Arctic plants traveled southward in every direction during the centuries of a glacial period, they would convey to both the Old World and to the New a vegetation of the same character. Thus we should find, during a glacial epoch, the lowlands of the temperate regions all round the hemisphere inhabited by plants possessing the characteristics of the Arctic flora at the present day.

Let us now suppose that the long period of glaciation is drawing to a close, and that more genial conditions begin to prevail. The Arctic flora becomes uncomfortable, and at length has to fly from a climate too kindly to suit it. But whither are the plants to go? Naturally the main line of retreat will lie toward the Pole, where the conditions they desire will be afforded them. But there will also be another means of escape. From the warmth of the lowlands the plants can retreat up the slopes of the mountains until at the summits they find those conditions to which they are adapted. The lowlands thus deserted by the Arctic flora, and with a hospitable climate restored, will again welcome back the ordinary temperate plants which had fled to the South at the beginning of the glacial epoch. These plants resume their old homes, and the earth regains its normal appearance, while on the summits of the lofty mountains vestiges of the Arctic flora continue to flourish.

It is thus shown that the phenomena of distribution of Alpine plants have corroborated the general arguments by which the former existence of a glacial period has been established. It is true that we scarcely wanted corroboration as to this particular, the records of the rocks and the presence of the bowlder clay and erratic bowlders supplied evidence too indisputable to need extraneous support. It is, however, interesting to note that delicate plants tell the same story as mighty bowlders weighing hundreds of tons. I have, however, introduced the subject of botanical distribution, not alone because it throws light on the elementary fact that Ice Ages have existed, but for a far more important reason.

We have already mentioned as an important consequence of the Astronomical theory that the glaciation oscillated between one hemisphere and the other; it is especially as to this point that the botanical evidence is instructive. We have the high authority of Sir J. Hooker for the remarkable fact that a great number of the flowering plants in Patagonia are either identical with, or are closely allied to, plants in temperate North America and Europe. To realize the significance of this fact, consider not so much that Patagonia and Northern Europe are separated by thousands of miles of land and sea, as that between them lies the torrid zone, in which these plants adapted to temperate regions could not live. There is no continuity between the flora of Patagonia and that of North America, for equatorial America is a barrier through which such organisms could not pass. How, then, are we to explain the community of botanical forms in two regions so remote? It is impossible to believe that these separate floras can have sprung independently into being, for all the analogies of nature demonstrate that they must have had some common source. The glacial theory is at hand to render an explanation of the facts.

Let us once again suppose that a glacial period is approaching in the Northern Hemisphere. We have already seen how the plants which normally reside in the temperate regions would be gradually compelled to travel southward, so that a large number of temperate forms would spread through equatorial regions. In all such arguments we must remember the long duration of the glacial periods, so that during the lapse of thousands of years certain species of plants may have become dispersed over wide ranges when the conditions offered are suitable. At such a time, according to Croll's theory, the Southern Hemisphere would be in that mild genial condition which alternates with the glacial epoch. Let us suppose that the glaciation of the Northern Hemisphere has run its course, and that a genial condition of things has returned. Normal heat is restored to the torrid regions; the temperate forms to which such warmth is ungrateful must retreat; some of them fly back to the temperate zones of the Northern Hemisphere, others escape to the summits of the lofty mountains, which even in the tropics, under normal conditions, will afford the climate they enjoy. But now a glaciation begins to grip the Southern Hemisphere: the temperate forms fly southward to the equatorial regions; the plants on the summits of the mountains begin to steal down the sides and to spread over the lowlands, which now attract them with a suitable climate, there they commingle with the temperate forms which have retreated before the glaciation in the Southern Hemisphere. Again, after a few thousands of years the glaciation is about to release its hold, the temperate forms are driven away before the increasing heat of the Equator, and are inclined to return to the zones which they had originally left. Thither they accordingly go, bearing with them some of the forms which came from the summits of tropical mountains; and thus the Northern forms at first isolated on tropical mountain tops are thence carried into the Southern Hemisphere. By this means we are able to explain how the plants in Patagonia have an unmistakable affinity with the plants in temperate regions of the Northern Hemisphere.

There is another circumstance in the distribution of plants which receives its explanation at the same time. On the summits of lofty mountains in the tropics certain plants find a habitat which the adjoining lowlands would not afford. It is remarkable that the flora of the summits of these tropical mountains all round the world have certain common characteristics, and this can likewise be explained.

Darwin mentions a group of facts which seem to make it certain that a mild, temperate climate must have occasionally encircled the earth at the Equator; for how otherwise could we account for the circumstance that the plants in the high lands across equatorial Africa, India, Ceylon, the Malay Archipelago, and in some degree across tropical South America, possess common features resembling those of a temperate flora, consisting of plants that could not live on the intervening lowlands. Here we have a demonstration of that critical doctrine in the Astronomical theory of the Ice Age which asserts that the Equator must have been occasionally visited by a temperate climate.

It would render the utmost assistance to the investigation of this subject to obtain whatever evidence may be forthcoming as to the existence of recognizable indications of glaciation through the various geological formations. That there are such indications to be had seems admitted, but here is one of those cases in which the imperfection of the geological record has most frequently to be regretted. I can only say that a strict search for glacial indications among all deposits, primary, secondary, and tertiary, would be one of the most valuable pieces of scientific work possible at the present time.

CHAPTER VIII.

CONCLUDING CHAPTER.

So long as a glaciated stone lies softly surrounded by the bowlder clay, its peculiar tracery is preserved. Let the protective covering be once removed, let the ice-engraved stone be rolled in the shingle on the sea beach, and presently its inscriptions are obliterated, and the record of its glacial origin is destroyed. The sheets of bowlder clay themselves are of a perishable nature, and liable to be washed away. The marks on glacier-eroded valleys have no greater permanence than the surfaces of the rocks on which they are written; wind and weather will at last crumble the mightiest erratics into dust. The advent of one ice-sheet plows away the traces of preceding ice-sheets, while the greater transformations that have been experienced during geological times are generally adequate to efface indications of such merely transient phenomena as the coming and the going of Ice Ages. It is not surprising, therefore, that the records of the rocks should be so imperfect as we find them when we come to investigate the glacial phenomena of former times. That there have been Ice Ages and Ice Ages hardly admits of a question; but to prove their sequence through geological time is difficult in the extreme, while to determine their number by the observation of geological phenomena is hopelessly impossible. It is one advantage of the Astronomical theory of Ice Ages that it exhibits the sequence of the phenomena in such a way as to suggest the kind of geological facts that seem likely to bear on the subject.

We have seen that, according to the Astronomical theory, the succession of Ice Ages takes place in this wise. The earth's orbit must first assume a high degree of eccentricity: so long as the eccentricity of the orbit is sufficiently high an Ice Age will be possible, provided the other condition is fulfilled. This other condition is, of course, that the position of the line of equinoxes shall be perpendicular to the major axis of the earth's orbit, so as to make the inequality between the duration of the two seasons as great as is compatible with the eccentricity at the time. There are thus two conditions contributory to the formation of an Ice Age, one lying in the state of the eccentricity, and the other in the position of the line of equinoxes.

There is a somewhat more simple method of investigating the conditions of the question. The really essential point necessary for the production of an Ice Age in one hemisphere, and the simultaneous production of a Genial Age in the opposite hemisphere, can be entirely expressed by the difference in the lengths of the seasons. The essence of the Astronomical theory resides in the fact that the total heat from the sun received during the summer in one hemisphere is a constant, and that the total heat received during the winter is also a constant. The highest degree of contrast between the climatic conditions of the two seasons is, therefore, obtained by making the difference in their durations as great as possible. The critical magnitude which decides whether a certain year is a glacial year or not simply depends, according to the Astronomical theory, on the difference between the lengths of the seasons in that year. Viewing the question in this way greatly simplifies the matter. The differences between the lengths of the seasons is, as a mathematician would say, a function of two other independent quantities; it partly depends upon the eccentricity of the earth's orbit, and partly on the longitude of the perihelion, that is to say, on the position of the line of equinoxes with respect to the longer axis of the earth's orbit; if there were no eccentricity there could be no difference in the lengths of the seasons, no matter where the line of equinoxes may lie. On the other hand, no matter what the eccentricity may be, there would be no difference in the lengths of the seasons if the line of equinoxes passed through perihelion. Taking the eccentricity and the longitude of the perihelion as they are found at any moment, the number of days in the difference of the seasons is a determined quantity. It fortunately happens for our present investigation that the only element we require is the difference in the duration of the seasons; we need, therefore, only consider the joint effect of eccentricity and position of perihelion as estimated in the single element of the difference in the lengths of the seasons arising from their joint influence.

We have already seen that the number 33 expresses the maximum number of days that by a combination of favorable circumstances expresses the difference in the duration of summer and winter respectively. From this maximum the difference may descend step by step to its present value of seven days, or to zero, in which the two seasons are of equal duration. The greater the difference the more intense becomes the contrast between the climatic conditions of the two hemispheres. That hemisphere which has the long summer and the short winter will be in a genial condition, while that with the short summer and the long winter will be glaciated. Other things being equal, we may certainly affirm that the greater the number of days in this difference the more intense will be the severity of the corresponding Ice Age.

So long as the eccentricity of the earth's orbit remains at its present value the difference between the lengths of the seasons will fluctuate between the extreme values of a winter seven days longer than a summer, and a summer seven days longer than a winter. But between these limits there can be no Ice Age; if there were a possibility of such, our Southern Hemisphere should be at this moment in a glacial state, and, of course, the Northern Hemisphere in a correspondingly genial state.

It is only, however, when the difference between the lengths of the seasons becomes much more considerable that an Ice Age proper may be the result. We have no means of knowing what relation may exist between the latitudes at which ice-sheets remain permanent from year to year, and the corresponding difference in the duration of the seasons. A perfect theory of Ice Ages should, of course, provide some information on this point; for the present, however, it will be sufficient to remark that when the difference, which is at present only seven days, makes some considerable approach toward its maximum value, which is nearly five weeks, then our globe is placed in that interesting condition in which Ice Ages and Genial Ages oscillate between one hemisphere and the other; the interval between the time of the maximum of glaciation and the maximum of the opposite condition in either hemisphere being 10,500 years.

I have spoken chiefly of those recent Ice Ages which have engraved their marks on the mountain flanks, and which have deposited sheets of bowlder clay over so large an area of the temperate regions. It is, however, an interesting consequence of the Astronomical theory that the causes which produce them may arise again. We have good grounds for believing that the general arrangement of our solar system has been substantially the same as it is at present, throughout the range of time indicated by the ordinary chronology of geology. No one imagines, for instance, that the planet Jupiter, as we know him to-day, revolved in an orbit, during the Silurian period, which differed to any considerable extent from the orbit which he now follows through the skies. Venus and Saturn then, doubtless, described orbits very much like those which they follow at present. On the other hand, no one supposes that the configurations of our system are absolutely eternal. Lagrange's theorems on the stability of the solar system go not so far as that. We are entitled to believe that, vast as are the eras contemplated by geology, they are yet small in comparison with the periods that would be required, before the evolution through which our solar system is progressing shall have succeeded in effecting any fundamental dislocation of the planetary orbits. We can not, therefore, doubt that the perturbations of the earth's orbit were produced in early geological times much as they are at present. There is no reason to think that the length of the year has ever been appreciably different within geological times from the length of the year as it now glides by; indeed, one of the most beautiful of Lagrange's discoveries was that which proved the inability of planetary perturbations to affect, permanently, the length of the major axis of the earth's orbit —at least, if the bodies be regarded as solid. Kepler's law asserts that the periodic times of planets and the lengths of their major axes are so connected that one could not alter if the other remained unchanged. As the major axis of a planetary orbit is unaltered by perturbation, it follows that the period of that planet's revolution must be also free from interference by the other planets. In early geological times, though the year may have been what it is at present, yet the seasons then, as now, changed their relative durations as an immediate consequence of perturbation. We have seen how the last Ice Age might be immediately attributed to a disparity in the lengths of the seasons, combined with the law of the distribution of heat between the two seasons. Similar influences were at work during remote geological epochs, hence we are entitled to infer, as a necessary consequence of the Astronomical theory, that throughout the whole period spoken of as geological time, Ice Ages have from time to time recurred according to a law of succession prescribed by astronomical conditions.

It is not, however, to be presumed that Ice Ages occur in any steady sequence at definite intervals of time, nor that when they do occur they are all of the same intensity. The intervals between their recurrence may, it is true, be not unfrequently 21,000 years, but the period will often be far greater. I may for the moment illustrate this point by referring to the laws of recurrence of the transits of Venus across the sun. There was one in 1874 and another in 1882 at an interval of eight years. There will not, however, be another until 2004, and then there will be another in 2012. In other words, the transits of Venus usually, but not always, occur in pairs, the two being separated by eight years, and then there is a long and variable interval of more than a century between one pair and the next. All this is well understood by the astronomer. There is a certain regularity in the recurrence of the transits of Venus, for we are able to calculate those that will happen for thousands of years to come. There is, however, no definite numerical relation between the successive recurrences that can be readily stated. When the transits of Venus do occur they present every variety as to duration and as to the regions on our globe from which they may be seen.

In these respects we may find a resemblance between the recurrence of the Ice Ages and the recurrence of the transits of Venus. Transits of Venus do not occur every eight years, and the planet does not always pass centrally across the sun, nor is it always visible from Greenwich. So it is with regard to Ice Ages; they do not recur every 21,000 years, they are not always equally severe, nor are their geographical effects always the same. The only general fact that can be stated with regard to the recurrence of transits of Venus is that they generally appear in pairs. The corresponding fact with regard to Ice Ages is that they generally appear in groups of two or more, the intervals between the consecutive members of the group being 21,000 years. More than this as to the epochs of recurrence of Ice Ages I have not asserted. I can not say when the last took place nor when the next may be expected. No one who is competent to deal with mathematical formulæ would venture on such a prediction in the present state of our knowledge. All we know is that the interval between two groups of Ice Ages seems to be generally enormously long as compared with the 21,000-year interval at which they follow each other in the group. And then as to the group of Ice Ages when it does come. At first, perhaps, the glaciation may be slight, and will increase with each recurrent 21,000 years until it reaches the maximum for that group. But the maximum of the group may fall far short of the maximum that may be possible in some other group by a different combination of circumstances.

It is so important to realize the variety of possible forms of Ice Age that the Astronomical theory offers, that I propose to go a little into detail. In order to illustrate the argument it has generally seemed best to take the most extreme case possible, in which the difference between the length of the seasons has its greatest possible value of thirty-three days; but the whole phenomena are graduated from this maximum to the present condition of the earth, in which the difference in the length of the seasons is but seven days. This does not seem enough to produce anything worthy of the name of an Ice Age. So far as it goes, however, it would indicate that the Southern Hemisphere had a slight tendency toward an Ice Age at present, and the Northern Hemisphere a tendency toward a Genial Age. In 10,500 years from the present time the winter in the Northern Hemisphere will be about seven days longer than the summer; then the tendency toward a glacial period will be met with in the Northern Hemisphere, and the Southern will tend toward the genial period. The possible difference in the length of the seasons in some other phase of the earth's orbit may be, let us say, twenty days. This will continue long enough to admit of two or more oscillations, so that the glacial and genial garbs shall be interchanged between the two hemispheres. What the severity of the glaciation might be under such circumstances it would be hard to say, but it would clearly be of a milder type than when the greatest possible difference between the seasons was obtained, other things remaining the same.

The Astronomical theory offers to us a vista of Ice Ages at irregular intervals and of varied severity. We are to expect neither uniformity in recurrence nor uniformity in intensity. This must be carefully kept in view when we come to seek records in the rocks as to the existence of past Ice Ages. It must also be borne in mind that the astronomical forces will necessarily blend with the other agents which have been invoked for the explanation of Ice Ages in past times. The effects produced by glaciation will, of course, be largely dependent on the disposition of land and water which may happen to constitute the geography of the hemisphere at the time of the glacial invasion; while, of course, the position of the high-lying lands will also be of much importance. The ocean currents, it need hardly be added, will be among the agencies which affect the distribution of the ice, and these are primarily influenced by the contour of the coasts. The presence of forests as a climatic influence contributes a further element of variety to the recurring Ice Ages during geological time.

From the consideration both of astronomy and of geology alike, it is thus evident that we can lay down no hard and fast lines as to when Ice Ages have occurred, nor as to their severity when they did occur. We can lay down no hard and fast lines as to what the glaciation may have been able to do and what tasks lay beyond its accomplishment. In seeking for traces of former Ice Ages we are beset with many difficulties, and there are not a few pitfalls in the path of him who would rashly approach this subject. Special instances seem full of peril. To say that this is the product of a Genial Age, and that of a Glacial Age, is sometimes tempting, but generally dangerous. The modifying circumstances are but partly known, or more often wholly unknown. That things are not what they seem is, in this case at all events, a maxim that should be carefully respected.

It is only in the most general and the broadest sense that I propose to summon the facts of geology to bear testimony to the doctrine expounded in this book. If there be one fact that seems beyond dispute, it is that the earth has undergone great changes in climate from time to time during its past history. The testimony of the rocks is here at least certain. That what we call climate is a highly complex system of conditions is, of course, admitted; but we are, I think, entitled to suggest that the thermal irregularities of which astronomy demonstrates the existence can not be disconnected from those changes in climate which geologists universally recognize.

Let us consider one of the most patent of all geological facts, which seems not improbably connected with glacial phenomena during the times that the sedimentary rocks of various ages were in process of formation. I will introduce the subject by a brief investigation of the kind of geological phenomena which such rocks ought to present if the Astronomical theory of an Ice Age be really the true one.

I shall, therefore, suppose that a time has arrived when the eccentricity of the earth's orbit has attained a value in or about the greatest that it can possibly reach. For a period of time, which is doubtless to be reckoned by many tens of thousands of years, this eccentricity remains sensibly constant, or at all events great enough to satisfy the condition requisite for glaciation. Let us suppose that it is the Northern Hemisphere which is glaciated and the Southern Hemisphere which is genial. In 10,500 years the condition has been reversed, and the Southern Hemisphere is glaciated and the Northern Hemisphere is genial; yet another 10,500 years, and the interchange has once again taken place. We shall suppose that this grand oscillation has been repeated two, three, or more times before the decline in the eccentricity of the earth's orbit shall have deprived us of a necessary factor in the production of a considerable Ice Age; it is surely reasonable to investigate the relation which these coming and going Ice Ages bear to that chiefest of geological operations, the manufacture of stratified rocks.

Let us briefly recall the process employed in their production. Rain washes the soil into the rivulets which combine to form a river. The waters enter the sea, and there deposit along the floor of the ocean the materials that they have brought down. Other agents contribute to the efficiency of the process. Frosts loosen and crumble the solid materials, and floods largely augment the quantities transported by the river. The more potent the agents by which the materials of the earth's crust are pulverized, the more rapidly will the rivers be able to supply the material which is gradually consolidating into stone at the bottom of the sea. In an earlier part of this book I had occasion to describe the force exerted by a glacier creeping down an Alpine valley, and I had also to point out how the same engine for grinding rocks into mud would be exhibited on a much grander scale in a country covered by an ice-sheet. The creeping of an ice-sheet over Greenland, for instance, must daily produce an enormous bulk of material ground and prepared for the formation of stratified rock, if only the necessary vehicle for conveying it down to the seas can be obtained. As the ordinary agents in the process of comminuting rock must necessarily be affected by the presence of ice, it is difficult to believe that the manufacture of stratified rocks proceeds at a rate which is independent of glacial phenomena. If our hemisphere were alternately in a glacial state and in a genial state, at periods separated by intervals of 10,500 years, it is only reasonable to expect that there shall be corresponding variations in the rate of production of stratified rocks. No doubt the questions involved are by no means of a simple nature; it seems probable that more material would be ground up during a glacial period than during a genial one; but there is also the problem as to the means by which this material is transported to the ocean. It may well be, that the time when the grinding machinery was at its utmost efficiency was not at all the same time as that at which the agents for transportation were best able to cope with their work. I do not, therefore, assert that it was actually during the maximum of a Glacial Period that the maximum amount of stratified rock was formed, as this is really unnecessary for our argument. The point which I especially desire to note is, that there must have been a species of rhythm in the manufacture of the stratified rocks, corresponding to the rhythm with which glacial periods and genial periods succeed each other.

The subject may be illustrated by what happens in the growth of a tree. During winter the vital operations in the tree seem quiescent, but in the spring there is the putting forth of the leaf, and during the summer and the autumn every leaf is a laboratory in which woody tissue is being prepared to add to the growth of the tree. The work of the leaf done, it withers and falls, and a second period of inaction is again entered upon. When the tree is cut down the series of rings which its timber shows are an indication of the various seasons through which the tree has passed. Were the growth of the tree continuous, then such rings would not be found. The greater the contrast between the seasons the more strikingly is this subdivision manifested.

At a time of maximum eccentricity the earth is subjected to marked changes in seasons. A perennial summer of 10,500 years in one hemisphere is gradually replaced by a winter of equal duration, to be again followed by another summer, and by subsequent repetitions for so long as the requisite conditions shall prevail. We might naturally expect that in the growth of stratified rocks some indications at least may be found of a rhythmical movement not wholly unlike that in the growth of a tree. Provided with this conception, let us now approach the actual facts of geology and see what they have to show us.

It would appear that one of the most familiar of all geological facts confirms the conclusion to which our reasoning has led. The quarry or the railway cutting presents us with a fact of obvious bearing on the question at issue. Were the conditions by which stratified rocks are manufactured uniform in their action, then we might reasonably anticipate that the masses of rock would be a continuous mass of a thickness corresponding to the length of time during which the uniform conditions prevailed. No doubt we do frequently see beds of stratified rock of great thickness, but surely every one who has devoted even casual attention to such matters will have noticed that the rocks in a quarry or the rocks in a railway cutting are usually arranged in a series of layers. From inspection of such sections it is obvious that a certain system of conditions prevailed while the first of these beds was being deposited, that then some considerable changes took place by which the deposition was interrupted. The original condition, however, recurred, and the second bed of rock was produced. Another interruption took place, and again the original conditions were restored. By subsequent repetitions one bed after another was produced until the whole system was formed. Of course it is not pretended that there is an absolute identity between the products of one period of active rock-making and that by which it was followed or by which it was preceded; for that matter the signs of growth in an ordinary tree show individual differences corresponding to the varieties of the seasons. We must similarly expect that there will be corresponding differences between the successive beds of rock, which, however, still preserve a generic resemblance.

The same phenomenon is generally to be seen wherever a section of aqueous rocks is exposed. We observe one bed of rock laid upon another often separated by intervening beds of different materials. We often find a repetition of a rock clearly similar or identical occurring in other beds higher up or lower down. This subdivision of the beds demands some special explanation. Why is it, for instance, that after a bed of one particular description has been laid down, the process has been interrupted, and that then it has been repeated with materials identical with or different from those in the first instance? What causes these interruptions? They must correspond to some disorganization of the agents by which aqueous rocks are manufactured. Now the doctrine of frequent Ice Ages variable in intensity and in the periods of their recurrence can hardly be overlooked in this connection. I certainly make no attempt to harmonize the successive beds with the recurrent Ice Ages. Such an attempt would be precarious in the extreme when we remember the numerous factors that must enter into the question; but that the recurrent Ice Ages are in some manner connected with this primary geological fact it seems hardly possible to doubt.

In bringing this work to a conclusion it is necessary to add that the agencies by which Ice Ages have been produced are still in operation. At present the difference between the length of the seasons is, as we have already stated, seven days. It so happens that the present position of the perihelion of the earth's orbit is such that the seasonal difference is near its maximum for the present eccentricity of the orbit. The precession of the equinoxes will gradually alter the relative lengths of the seasons. From being unequal, as they are at present, they will approach to equality, and then at the other end of the swing the summer in the Northern Hemisphere will be seven days shorter than the winter in the same hemisphere, instead of being as much longer. Again, the oscillation will carry the seasons back to what they are at present, so that in 21,000 years or so the summer will just exceed the winter by seven days, as it does now. Ice Ages are, however, not to be expected from vicissitudes such as those which are at present possible. This 21,000-year period which swings to and fro will, however, prevail independently of the changes in the eccentricity. The perturbations by which those changes can be produced will, doubtless, exist in the future as they have done in the past, if the present order of nature be preserved. It will therefore follow that, in the distant future, the eccentricity will attain so high a value that the difference between the duration of the seasons will rise to the point at which the phenomena of glaciation are produced. Nor is there any reason for thinking that there will only be a single occasion on which the eccentricity shall rise to a sufficiently high point. Just as there have been several maxima in the course of ages past, so we may infer from mathematical laws that there will be several maxima of eccentricity in time to come. Calculation leaves no doubt on this point, although it does not, however, inform us, with any degree of certainty, as to the immense periods that must elapse before the first of these phases of high eccentricity will return. It is, however, a consequence of the Astronomical theory of Ice Ages that they must return in the future. There is, therefore, the best of reasons for believing that as these temperate regions have been submerged on various occasions, in past ages, beneath ice-sheets a thousand feet or more in thickness, so in future periods the ice-sheets will again return and desolate those regions which now contain the most civilized nations of the earth.

The ancients consulted the stars for the purpose of reading in their movements the vicissitudes of human affairs. Astrologers cast their horoscopes, and showed how the career of the man was predicted in the configuration of the planets at his birth. Statesmen sought the stars for guidance in the affairs of the empire; while a decision on all matters of moment could only be safely taken after consultation with the heavens. We now smile at the credulity of those who put faith in the astrologers. We certainly do not now believe that the positions of the planets are to be taken as prognostications which convey a direction from heaven for the benefit of those who seek it. We do not any longer believe that Mercury and Venus, Mars, Jupiter, and Saturn, were placed in the heavens for the sole purpose of prophesying weal or threatening woe to mankind. In the fifteenth century it happened that three planets came into a remarkable relation, according to the received notions at the time. Such an occurrence must portend something; what that was, the astrologers discovered by noticing that the conjunction took place in a watery sign. The interpretation was now obvious. Floods of water were of course to drown Europe beneath their dismal expanse. The consternation was wide-spread at the prospect of this second deluge, and rafts and life-buoys were got ready everywhere. Voltaire tells us of a doctor of Toulouse who, having bought a boat for himself, fortunately remembered that if his patients were all drowned his medical practice would experience a corresponding limitation; the prudent physician accordingly built a gigantic ark for the reception of his patrons and for the security of his professional income. Happily, the doctor's fears were not realized; the great flood did not come off. Long practice in many similar emergencies had rendered the astrologers quite equal to the occasion; they explained how the deluge had been arrested by a fortunate dispensation, which I recount in their own words:

"Saturn disposes of the sun, who is posited in the terms of Venus, and Venus and Saturn and the Moon are all disposed of by the benevolent planet Jupiter, who is himself disposed of by Mars, the principal significator."

It is, therefore, obvious that the reason why the deluge should have come and the reason why it failed to come are both accounted for on equally satisfactory principles. Yet, strange to say, all this nonsense about the planets and their influence on terrestrial affairs seems to possess a certain affinity with a great scientific truth. No one now believes that any particular configuration in which the planets may happen to lie, portends a pestilence, a war, or a deluge of water, but the truth is much more striking than the wildest fiction of which astrologers ever dreamed. Those who have followed these pages will have learned that, according to the Astronomical theory herein set forth, the influence of the planets has occasionally visited some of the fairest regions of our globe with a scourge more deadly than the most malignant pestilence, more destructive than the most protracted of wars, and more desolating than the mightiest of floods.

Slumbering in the Arctic regions lies at this moment the agent of the most dire of calamities. That agent has once, and more than once, been aroused into activity. Time after time it has happened that the planets have by their influence on the earth's orbit brought down on our temperate regions the devastations of the great ice-sheet. From its normal home at the Poles the great glaciation has spread southward; a sheet of ice and snow hundreds or thousands of feet thick has crept from the highlands of Norway and Sweden, has invaded Central Europe as far as Saxony, while the greater part of Great Britain was also submerged by an icy covering. Nor did the New World afford a refuge from the frightful inclemency. Wide-spread sheets of ice of enormous thickness submerged Canada, and buried much of that tract which now forms the Eastern States.

Did the imaginations of the old astrologers ever attribute to the operations of the planets any calamity at once so vast and so fatal? All that the astrologers have ever claimed for the influence of the planets seems trivial in comparison with the grim severity of the ice-sheet. The Astronomical theory of the Ice Age, however, assures us that it was the planets which drew down this icy invasion, and that it was the planets which bade the ice to withdraw. The influence of the planets followed the retreating ice within its natural confines in the Arctic circle, chased it entirely from the hemisphere, and permitted the horrors of the Ice Age to be forgotten in the joys of the summer by which it was succeeded. The planets indeed have been potent agents in human affairs.

The Astronomical theory of the Ice Age presents us with interesting thoughts as to the connection between our earth and the other planets. Accepting this doctrine, it is hardly possible to overestimate the influence which the planets have had in shaping our globe to the form in which we now find it. It seems hardly fanciful to say that we can recognize the handiwork of the planets everywhere around us. I commenced this little book with a reference to the Cloghvorra Stone on the Kenmare River, a picture of which forms a frontispiece to our volume. That this great bowlder was left where we now find it by the action of ice is a fact as to which doubt is impossible; it is one of the indications of the last severe Ice Age from which our country has suffered. It has been my object to set before you the reasons for thinking that the planets, and especially Jupiter and Venus, have been the primary agents in the formation of Ice Ages; we have substantial grounds for attributing to the agency of the planets the familiar indications of glaciation. When we gaze on the Cloghvorra Stone a fanciful person might almost think that it was the thews of mighty Jupiter himself which ripped that stone from its original bed, some miles away, and sportively cast it down on the mountain side. When, also, we examine the inscription on a glaciated stone, we need not dissociate the engraving from the planetary agents by whose operations it was ultimately produced. May we not imagine the characters on the stone as having been traced by the fair hand of Venus herself?

Finally, let me say, and, perhaps, in some degree repeat, what I have urged with regard to the claims of the Astronomical theory of the great Ice Age to our acceptance. Geology having taught us by unmistakable evidence that Ice Ages have happened, it is rational to inquire into the causes by which phenomena so startling have been brought about. We find that the Astronomical theory offers at once an explanation adequate to the effects which have been observed. We find that this theory involves no gratuitous assumptions, and that it does not require the co-operation of any agents except those with which we are already familiar. The theory is based on the movements of the heavenly bodies as we now actually find them. The dynamical relations of those movements are now so thoroughly understood by mathematicians that there is here no ground for doubt. We have shown that these necessary movements must be followed by profound climatic changes on this globe. We have even shown that the astronomical conditions are so definite that astronomers are entitled to direct that vigorous search be instituted on this globe to discover the traces of those vast climatic changes through which astronomy declares that our earth must have passed. When the astronomer, who is bent on this search, finds the geologist coming to seek from him an explanation of the climatic changes of which he has detected the evidence in the rocks, it seems impossible to deny that the labors both of geologists and of astronomers have in this case both illustrated and supplemented each other. The geologist has supplied the evidence which the astronomer wanted; the astronomer has supplied the explanation which the geologist wanted.

The Astronomical theory removes the glacial period from the position of a "catastrophic" phenomenon. It places the ice-sheet as an implement at the disposal of the geological uniformitarian, to be used with the other agents with whose powers he is already familiar.

APPENDIX.

THE following is the calculation so often referred to in this book, and in which for the first time, so far as I know, the astronomical facts relating to Ice Ages have been correctly given. I compute the total quantity of heat received by each hemisphere of the earth during summer and winter respectively as follows:

Let $2H/a^2$ be the quantity of sun heat falling perpendicularly on an area equal to the section of the earth at the mean distance a from the sun in the unit of time.

Let δ be the sun's north declination. Then the share received by the Northern Hemisphere will be

$$\frac{H}{a^2}(1 + \sin \delta),$$

and by the Southern

$$\frac{H}{a^2}(1 - \sin \delta).$$

At the distance r, and in the time dt, the heat received in the Northern Hemisphere will be

$$\frac{H}{r^2}(1 + \sin \delta) \,.\, dt;$$

but we have

$$r^2 \, d\theta = h dt,$$

whence the expression becomes

$$\frac{H}{h}(1 + \sin \delta) \,.\, d\theta;$$

but we have

$$\sin \delta = \sin \theta \,.\, \sin \epsilon,$$

where ϵ is the obliquity.

The total heat received by the Northern Hemisphere from the vernal to the autumnal equinox is

$$\int_o^\pi \frac{H}{h}(1 + \sin \epsilon \sin \theta) \, . \, d\theta = \frac{H}{h}(\pi + 2 \sin \epsilon).$$

We have thus the following theorem, which constitutes the essence of the Astronomical theory of an Ice Age, and to which I invite the reader's particular attention:

Let $2E$ be the total sun heat received in a year over the whole earth; then this is divided into shares as follows:

$$\text{Northern Hemisphere, summer, } E\frac{\pi + 2 \sin \epsilon}{2\pi}.$$

$$\text{“ \quad “ \quad winter, } E\frac{\pi - 2 \sin \epsilon}{2\pi},$$

with identical expressions for the summer and winter in the Southern Hemisphere.

If we make $\epsilon = 23° \ 27'$ we find that the heat received during the summer (equinox to equinox) of each hemisphere is ·627 E, while the heat during the winter of each hemisphere is ·373 E. More briefly still: If each hemisphere receives in the year a quantity of sun heat represented by 365 units, then 229 of these are during summer and 136 during winter. These figures are independent of the eccentricity of the earth's orbit.

The length of the summer is defined to be the interval when the sun's center is above the equator. The length will, of course, vary with the eccentricity and with the position of the equinoxes on the orbit. We need only take the extreme case where the line of equinoxes is perpendicular to the major axis of the orbit. The maximum difference between the length of summer and of winter is thus

465 days × eccentricity.

I take the maximum eccentricity of the earth's orbit to be

0·0745,

this being the mean of the values by Leverrier, Lagrange, and Stockwell, and, therefore, the greatest difference between summer and winter will be about 33 days—i. e., one season is 199 days, and the other is 166 days.

The total quantity of heat received during the year on each hemisphere is practically independent of the eccentricity; but the mode in which that heat is received at the different seasons will vary, and thus give rise to the following extreme cases, already referred to on page 102:

GLACIAL

229 heat units spread over 166 days.
136 heat units spread over 199 days.

OR INTERGLACIAL

229 heat units spread over 199 days.
136 heat units spread over 166 days.

We hence deduce the following, where unity represents the mean daily heat for the whole year on one hemisphere:

GLACIAL

Mean daily sun heat in summer (short) . .	1·38
Mean daily sun heat in winter (long) . .	·68

INTERGLACIAL

Mean daily sun heat in summer (long) . .	1·16
Mean daily sun heat in winter (short) . .	·81

PRESENT (NORTHERN HEMISPHERE)

Mean daily sun heat in summer (186 days) .	1·24
Mean daily sun heat in winter (179 days) . .	·75

These figures exhibit a thermal force of great intensity. The unit represents all the mean daily heat received from the sun by which the earth is warmed up from the temperature of space. The heat unit, in fact, maintains a temperature perhaps 300°, or even more, above what the earth would have without that heat. Each tenth of a unit may thus roughly be said to correspond to a rise or fall of mean temperature of 30° or more.

The long winter of 199 days, when the average heat is only two thirds of a unit, leads to the accumulation of ice and snow, which forms the glacial epoch. The short winter of 166 days, where the temperature is ·06 of a unit above that of our present winter, presents the condition necessary for the mild interglacial epoch.

INDEX.

THE END.